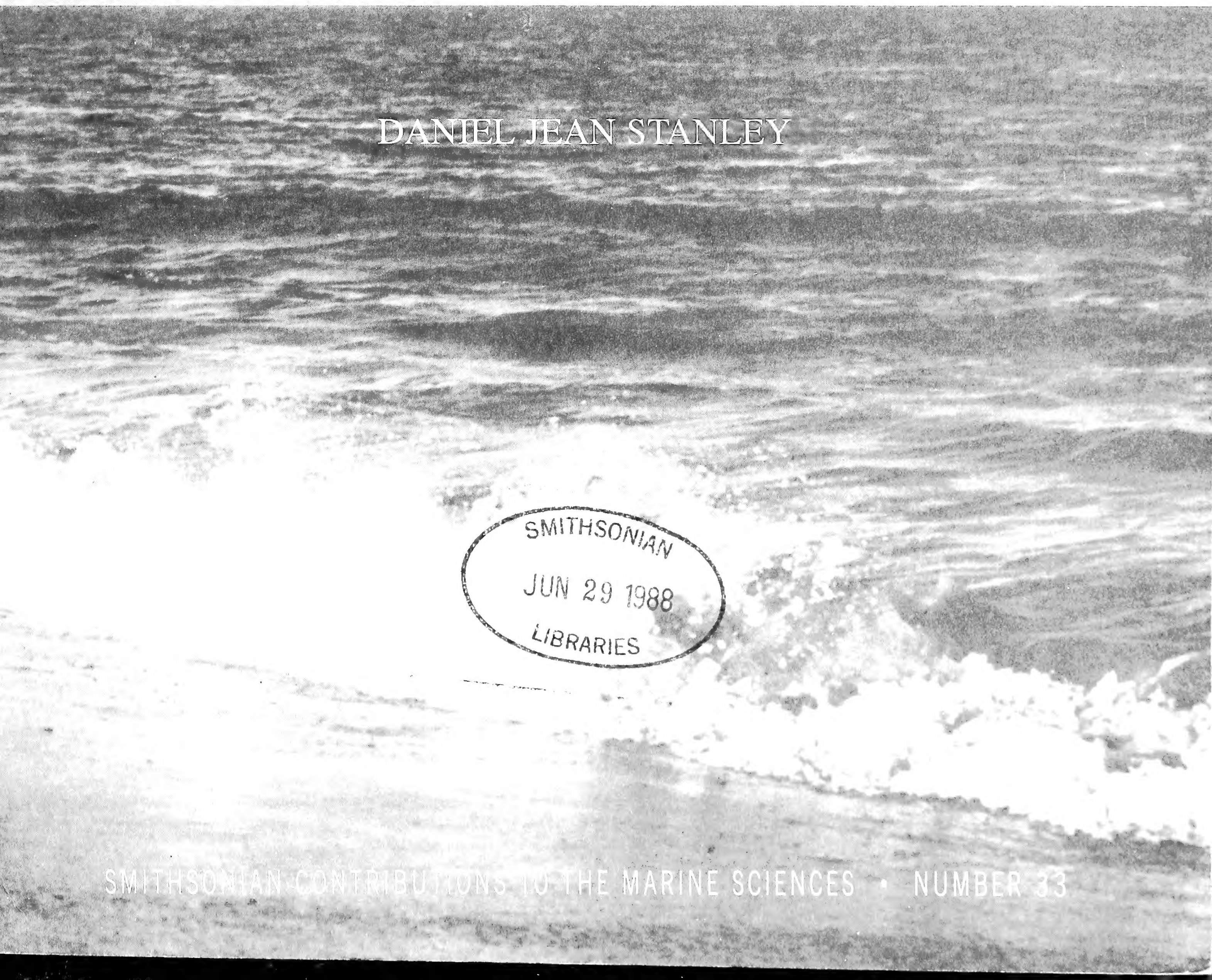
Turbidites Reworked by Bottom Currents: Upper Cretaceous Examples from St. Croix, U.S. Virgin Islands



DANIEL JEAN STANLEY

SMITHSONIAN CONTRIBUTIONS TO THE MARINE SCIENCES • NUMBER 33

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ABSTRACT

Stanley, Daniel Jean. Turbidites Reworked by Bottom Currents: Upper Cretaceous Examples from St. Croix, U.S. Virgin Islands. *Smithsonian Contributions to the Marine Sciences,* number 33, 79 pages, 63 figures, 3 tables, 1988.—Sedimentological study of the Late Cretaceous volcaniclastic deposits in St. Croix, U.S. Virgin Islands, emphasizing primary structures and bedforms, reveals a remarkable suite of sandy lithofacies. An inventory of the different sand types in several formations shows that a natural continuum of deposits exists between downslope-directed gravity flow and bottom current-tractive "end-member" deposits. Most sandy strata, herein termed "intermediate variants," record primary emplacement by turbidity currents, probably from the north, and a subsequent reworking of these layers by bottom currents flowing toward the west. The sand layers accumulated in a proximal setting, perhaps slope aprons, and these were then reworked along bathymetric contours. The lower portion of sand layers typically displays the original graded (A) turbidite division, while the texturally cleaner mid and upper parts of such strata usually show structures more typically associated with tractive transport. Photographs of polished slabs and large thin sections of the diverse Cretaceous sand layer types on St. Croix, reproduced at a 1:1 scale, may serve as a basis for comparison with other deep-water formations in the modern and ancient record. They may be most useful in interpreting sequences such as those on St. Croix where a solely turbidite or gravity-emplaced interpretation is inadequate.

This petrologic investigation also sheds further light on the paleogeography of the region. Examination of the sandy volcaniclastic sequences supports earlier hypotheses that they accumulated in a tectonically active island-arc setting. A strong tectonic and volcanic imprint is displayed by the syndepositional deformation of fabric, bedforms, and primary structures. Paleocurrent analyses indicate that, in what was to become the northeastern part of the Caribbean, the predominant bottom-current trend during Late Cretaceous time was roughly parallel to the surface circulation pattern, i.e., directed toward the west. The vigorous reworking of coarse sand and granule turbidites, and the development of bioturbation structures in tractive deposits indicate that, although the paleo-Atlantic was geographically much narrower, bottom-water circulation in this region was not restricted nor were bottom waters anoxic. Recognition here of the diverse suite of reworked sandy turbidite lithofacies, poorly documented to date, can hopefully serve to clarify other cases in both the modern and rock record where there has been interaction between bottom currents and turbidity currents.

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Contents

Turbidites Reworked by Bottom Currents: Upper Cretaceous Examples From St. Croix, U.S. Virgin Islands

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Introduction

This study examines the primary sedimentary structures of sandy marine deposits that appear to have been initially emplaced by turbidity currents and associated gravity flows, and then were subsequently reworked by bottom currents sweeping the seafloor at depths below wave-base. Most earlier investigations that deal with this topic have usually—and rationally—emphasized the contrasting characteristics of end-member sandy facies that can be used to distinguish well-defined turbidites from deposits essentially emplaced by bottom-current (Heezen and Hollister, 1971, ch. 8 and 9; Hollister and Heezen, 1972, table 2; Bouma and Hollister, 1973, table 1; and Stow and Lovell, 1979, tables II and V). This approach to the interpretation of depositional processes of deep-sea sands is admittedly much simplified and far from comprehensive, and sediment types are almost certainly more numerous and varied than has been described.

It is the premise of this investigation that sandy marine layers, which are intermediate, or transitional, variants between classic turbidites and strata reworked by well-defined bottom currents, are probably much more common and wide-spread than is generally recognized. Most publications treating sand transport processes in modern oceans and the deposition of deep marine sandstones preserved in the rock record usually do not detail or illustrate such intermediate facies. It follows from this that, in many cases, the transport origin of these depositional variants has been misinterpreted (usually as turbidites).

Hsü (1964:383) has suggested that the faulty identification of facies has probably caused confusion as well as error in a number of paleogeographic reconstructions. In the case of rock units that include both graded bedding and sandy layers deposited by bottom currents, it is logical to consider *intermediate variants* (that is, strata that show attributes of both facies) in order to better evaluate depositional conditions. In such instances, any thorough paleobasin study should include a rigorous assessment of the complete suite of primary physical and biogenic structures.

The present work details rock units in St. Croix, U.S. Virgin Islands in the northeastern Caribbean (Figure 1) which, to date, have been interpreted primarily as turbidites (Whetten, 1966b; Speed, 1974). This monograph illustrates the diverse assemblage of sedimentary and biogenic structures characteristic of the Upper Cretaceous (Campanian to Maestrichtian) Caledonia Formation and associated and volcaniclastic units exposed on St. Croix (Figure 2). Photographs of the major sedimentary and biogenic structures are reproduced, where possible, at a 1:1 scale. In addition to serving as an illustrative reference for the interpretation of deep-marine, sandy lithofacies and for sediment-transport analysis, this type of study may have paleogeographic value. For example, it could serve to refine, at least in a modest way, our understanding of the paleobasin conditions, including slope- and bottom-water circulation patterns, that occurred in this part of the Caribbean toward the end of the Cretaceous.

Acknowledgments.—The assistance of Messrs. L. Ford and H. Sheng, National Museum of Natural History (NMNH), Smithsonian Institution, in cutting and polishing rock slabs and making numerous large thin sections used in this study is appreciated. Thanks are also expressed to Mr. Sheng for his help in identification of minerals in thin section, separation of heavy minerals, and chemical and microprobe analyses of selected rock samples. Photos of the many polished rock slabs and thin sections were made by Mr. V.E. Krantz, Photographic Division, NMNH. Drafting was done by Ms. M. Parrish and typing by Ms. D. Larkie, both of the Department of Paleobiology, NMNH.

The West Indies Laboratory (W.I.L.) of Fairleigh Dickinson

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FIGURE 1.—Map showing location of St. Croix, largest of the U.S. Virgin Islands, in northeastern Caribbean Sea.

University at Teague Bay, St. Croix, U.S. Virgin Islands, kindly provided facilities and served as the supportive base from which I conducted this study during six field visits, from 1981 to 1986. Drs. R.F. Dill, former Director, and D.K. Hubbard, geologist, at W.I.L. were enthusiastic hosts who guided me during the early phases of the field investigation. Dr. Hubbard also generously provided several aerial photographs reproduced in this study, and provided a most helpful review of the manuscript. Drafts of the manuscript also were read by Drs. L.J. Doyle, University of South Florida, C.D. Hollister, Woods Hole Oceanographic Institution, and J.T. Whetten, Los Alamos National Laboratory. Funding for the study was provided by several Scholarly Studies Program awards through the Office of Dr. D. Challinor, Assistant Secretary for Research at the Smithsonian Institution.

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A Review of the Problem

In an important essay relating sedimentation to tectonics, E.B. Bailey, in 1930, called attention to, and contrasted, two well-defined and often distinct bedforms displayed by marine sandy sediments preserved in folded belts. He attributed cross-bedded and non-graded deposits to bottom-current transport processes; he attributed the other, strata showing graded bedding, to the settling of particles through comparatively still bottom water. In a later paper Bailey (1936:1716) concluded that "current-bedded sandstones belong to relatively shallow water (or to the air), and graded-bedded sandstones belong to relatively deep water." The past half century of research has shown these earlier ideas on marine sediment transport to be essentially in error.

The pioneer works by, among others, Kuenen (1937, 1938), Bell (1942), and Kuenen and Migliorini (1950), showed that gravity-driven turbidity currents are a major cause of graded bedding in sands. Since World War II the development of underwater photography and the means to measure the velocity and direction of current flow in deep water have led to an even clearer picture of deep-sea processes. For example, it has been clearly demonstrated that ripples, scour marks, and associated tractive-surface and internal-bedform features, including cross lamination typically produced by bottom currents, are widely prevalent on modern ocean margins and in basins at highly variable depths (Heezen and Hollister, 1971:335–421).

It is now generally recognized that graded bedding and stratification produced by tractive transport are not representative of essentially different, mutually exclusive sandstone facies as previously proposed. Rather, these two bedform types may be found together in a host of non-marine as well as marine settings, some as different as terrestrial flood plains (Stanley, 1968) and deep-water, base-of-slope, and lower rise environments (Stanley, 1969). In this respect, it should be added that Bailey (1936:1716) had astutely recognized that "sometimes there is an admixture of type, even within one and the same bed," i.e., graded and current bedding.

By the early 1950s, workers considered the rippled bedforms

sometimes associated with graded sequences as being produced, in some cases, by "dilute turbidity currents, of sufficient velocity to move a light bed load by traction" (Natland and Kuenen, 1951:106). Moreover, stratification such as foreset lamination, usually associated with bottom-current/tractive processes, became recognized as an integral part of turbidites by Kuenen and his associates (Kuenen and Menard, 1952:83; Kuenen, 1953:1051–1053; 1958:1018; Kuenen and Carozzi, 1953:364; Kuenen and Sanders, 1956:658; Kuenen and Humbert, 1969). Subsequently, Bouma (1962:49) described the more specific position occupied by current laminated layers in turbidite sequences, and Walker (1965:14–18) and others interpreted the hydrodynamic origin of this rippling phase as a natural part of a gravitative flow event. From about 1950 until the mid-1960s, the overwhelming majority of studies in both the ancient rock and modern-sediment records concluded that the emplacement of sandy layers in deep-marine deposits was by turbidity currents.

By 1970, the apparent distinction between laminated and rippled deep-sea sediments resulting from turbidity currents and those deposited by fluid-driven circulation was no longer an obvious one. It became progressively clear that a greater diversity of processes could be used to explain the depositional sequences found in the modern and ancient deep sea. A growing number of gravity-driven flow mechanisms were recognized as likely transport agents responsible for the downslope-basinward displacement of shallow-marine faunas and clastic particles to deeper environments (cf. Middleton and Hampton, 1973:3–30). During this same period, empirical calculations and theoretical modelling and subsequent verification by actual observation and in-situ measurements on the seafloor indicated the importance of moderate to powerful bottom currents driven by thermohaline circulation of water masses. The importance of deep-water masses sweeping extensive areas of the ocean floor, including lower bathyal and abyssal environments, was initially recognized by, among others, Wüst (1958), Ostapoff (1960), and Swallow and Worthington (1961). The phenomenon of deep-bottom currents flowing long distances over large surfaces of ocean seafloor is now generally accepted (Heezen and Hollister, 1971, chap. 9).

These physical oceanographic investigations coupled with the rapidly growing number of marine geological observations in the different world oceans have served to confirm the important role of deep-sea currents on sediment transport. Of particular significance is the potential role of deep currents in the reworking of turbidites. In this area of research three geological studies, all published in 1964, were particularly influential. (1) In modern oceanic environments, Heezen and Hollister (1964) recognized the importance of bottom currents on deep-sea transport and their role in redeposition. Their conclusions were based on bedforms recorded in bottom photographs along with physical structures displayed in deep-sea cores (actual examples of these were later amply illustrated in chapter 9 of the photographic atlas published by these authors in 1971). (2) Hubert (1964), who also recognized the significance of current bedding, identified textural attributes of deep-sea sands that he felt were indicative of reworking of sandy turbidites by bottom currents. (3) Hsü (1964) suggested that turbidites, after deposition, can be reworked by bottom currents. Citing examples in both the rock record and modern oceans, he based his conclusions on bedforms and associated primary sedimentary structures and textures, along with the presence of mixed shallow-water and deep-sea benthic faunas.

By the mid-1960s the pendulum, at least in the modern marine record, was swinging away from turbidite transport toward another pole: the concept that sandy deposits at depth were laid down by bottom currents. In a short incisive article Heezen et al. (1966) developed an extreme view, i.e., that thick masses of sediment forming continental rises, such as those on western margins of ocean basins, are built up primarily by contour-following currents. In the model presented, the currents are geostrophically driven and redistribute material originally emplaced by turbidity currents. This concept resulted in large part from a series of studies made on the Atlantic margin off northern North America. Subsequently, physical oceanographic and geologic considerations, pointing to the influence of large-scale water mass flow over the ocean floor, were integrated in a synthesis paper published by Hollister and Heezen in 1972.

It is now generally recognized that transport of sands to deep-marine environments is more complicated than proposed by either the turbidity-current or the bottom-current schools. Hsü (1964:379) had quite reasonably warned that "indiscriminate assumption of turbidity current deposition of all deep marine sandy sediments has led to confusion, inconsistencies and controversies." Unfortunately, another conceptual problem has evolved: in the majority of recent investigations, sand layers that display rippling and associated cross- and foreset-laminated structures have been related to fluid-driven circulation as the primary transport mechanism. Such rippled and cross-bedded sands have been termed "tractionites" by some workers (Unrug, 1977:365) and "contourites" by others (Hollister and Heezen, 1972:60). The latter term, more commonly used, is defined by Lovell and Stow (1981:349) as "a bed deposited or significantly reworked by a current that is persistent in time and space and flows along slope in relatively deep water (certainly below wave base). The water may be fresh or salt; the cause of the current is not necessarily critical to the application of the term." This interpretation for cross-bedded deep-sea sands, if indiscriminately applied, can also lead to confusion.

In the present monograph the use of these genetic terms (tractionite, contourite, winnowite) is avoided since the intent herein is to minimize confusion introduced by problems of semantics, and to clarify interpretations as to sediment transport of Cretaceous rocks in St. Croix. A useful approach to understand deep-sea sedimentation is one of comparative

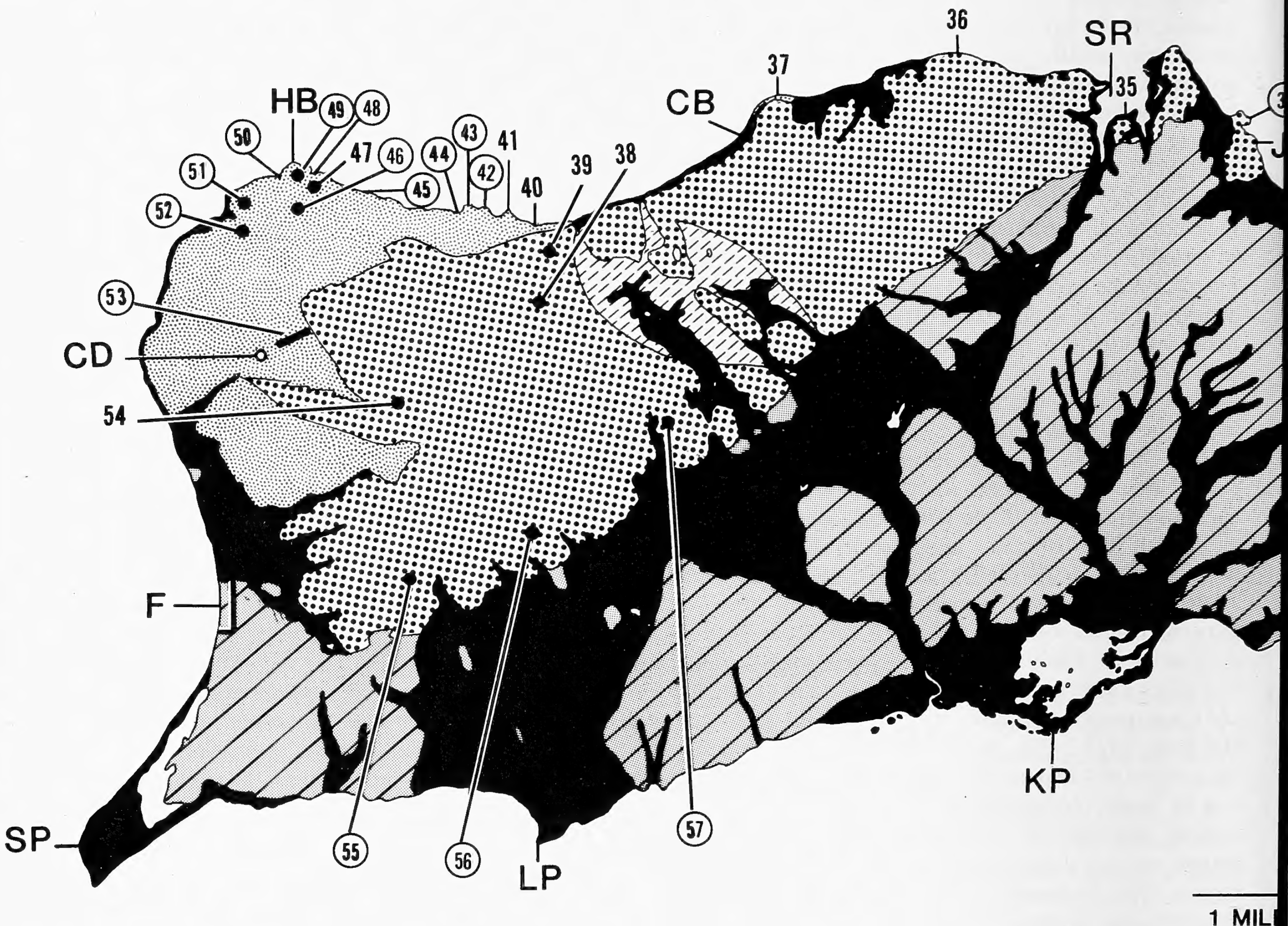
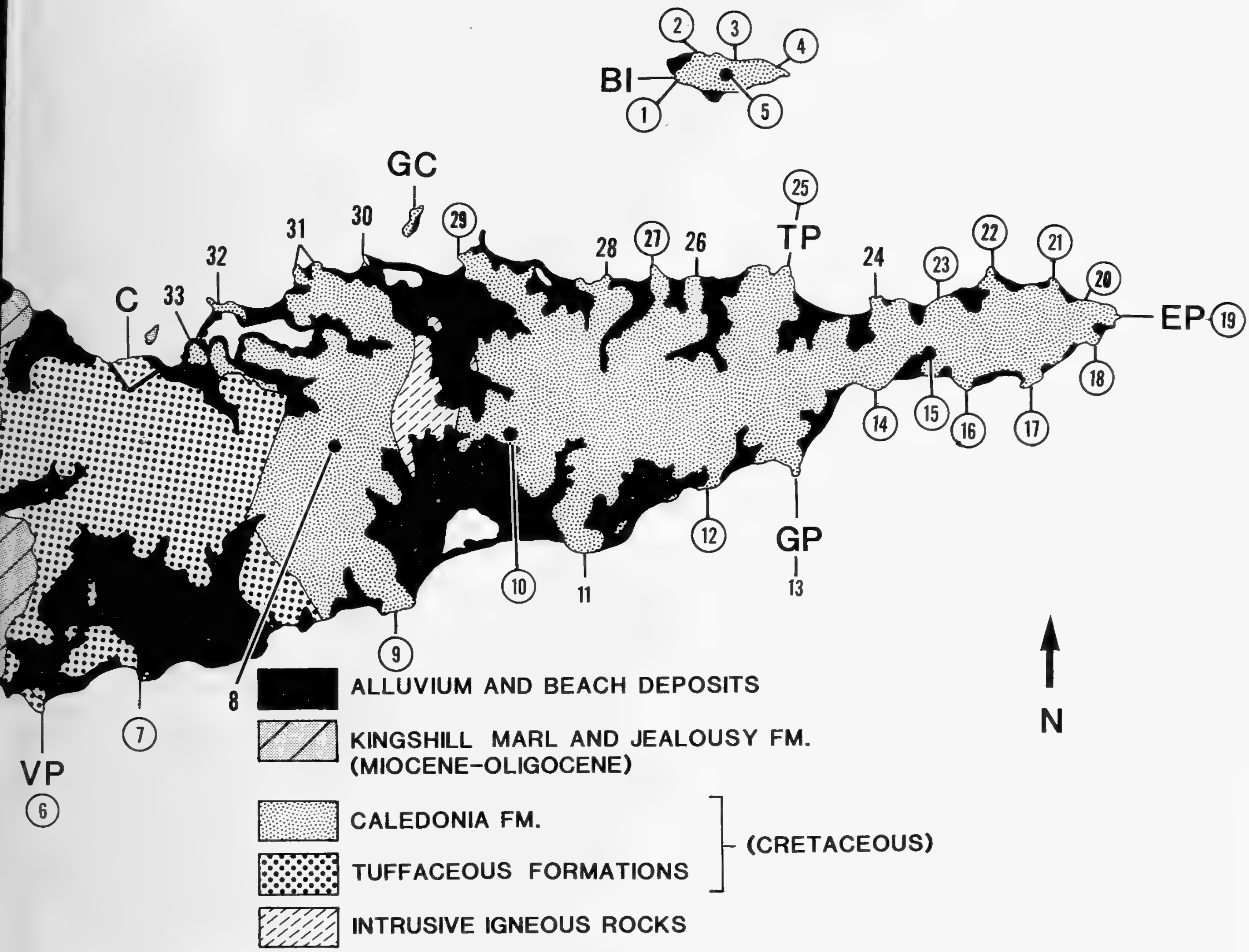


FIGURE 2.—Simplified geological map of St. Croix (modified after Whetten (1966b; 1974, fig. 1) showing 57 localities where samples were collected (geographic names of sites in Table 1 (below), and sample numbers in Table 2). Photographs of representative outcrop exposures, rock slabs, and thin sections presented in this study were selected from 38 localities (circled site number).

analysis. In this study, the characteristics of deep-sea sands emplaced or reworked by fluid-driven mechanisms are compared with diagnostic characters of those transported primarily by gravity-driven processes (cf. review article by Stow and Lovell, 1979). A series of publications have attempted to refine ways by which turbidites, which commonly display current lamination as an integral part of the accepted vertical succession of bedforms, can be distinguished from laminated sandy facies emplaced by bottom currents (Walker, 1965; Kuenen and Humbert, 1968; Unrug, 1977, 1980; Piper, 1978; Shanmugan and Walker, 1978; Stow and Shanmugan, 1980; Lovell and Stow, 1981). As it is often difficult to differentiate the depositional products from these two different transport mechanisms, most emphasis has been placed on contrasting, perhaps in an overly simplified or somewhat exaggerated manner, the graded turbidite and rippled, tractive, end-member facies.

The problem most likely encountered by geologists trying to interpret sandy layers in modern deep-marine environments and in the rock record is that some strata are neither of distinct turbidite origin nor emplaced entirely by bottom currents. It would be useful, therefore, to have available a photographic catalog illustrating the suite of sedimentary features displayed in these transitional sandy facies. It would also be particularly helpful if examples of such intermediate variants were selected from deposits where distinct sand turbidites and bottom-current



sequences occur together. Moreover, it would be more practical to consider the problem in the rock record, where strata can be traced along the outcrop and where strata are more extensively visible in samples recovered from modern oceans. In the latter case, observations are usually limited to narrow-diameter gravity and piston cores or wider diameter, but shallow, box cores.

In view of the above considerations, this monograph presents examples, many at a 1:1 scale, selected primarily from the Upper Cretaceous volcaniclastic Caledonia Formation, and associated tuffaceous (including Judith Fancy) sequences on St. Croix, U.S. Virgin Islands. These various units on St. Croix were selected because they comprise both gravity-driven and fluid-driven deposits. The rocks display a fairly extensive assemblage of sedimentary structures, and serve to highlight deep-marine facies that record the effects of more than one transport mechanism.

Methods

This study involved field work throughout most of St. Croix where Cretaceous rocks are exposed (Figure 2). Field work was conducted during six surveys: 6 to 15 February 1981; 12 to 21 January 1982; 9 to 21 March 1983; 2 to 13 February 1984; 7 to 16 February 1985; and 19 February to 2 March 1986. Numerous outcrop localities of Late Cretaceous age

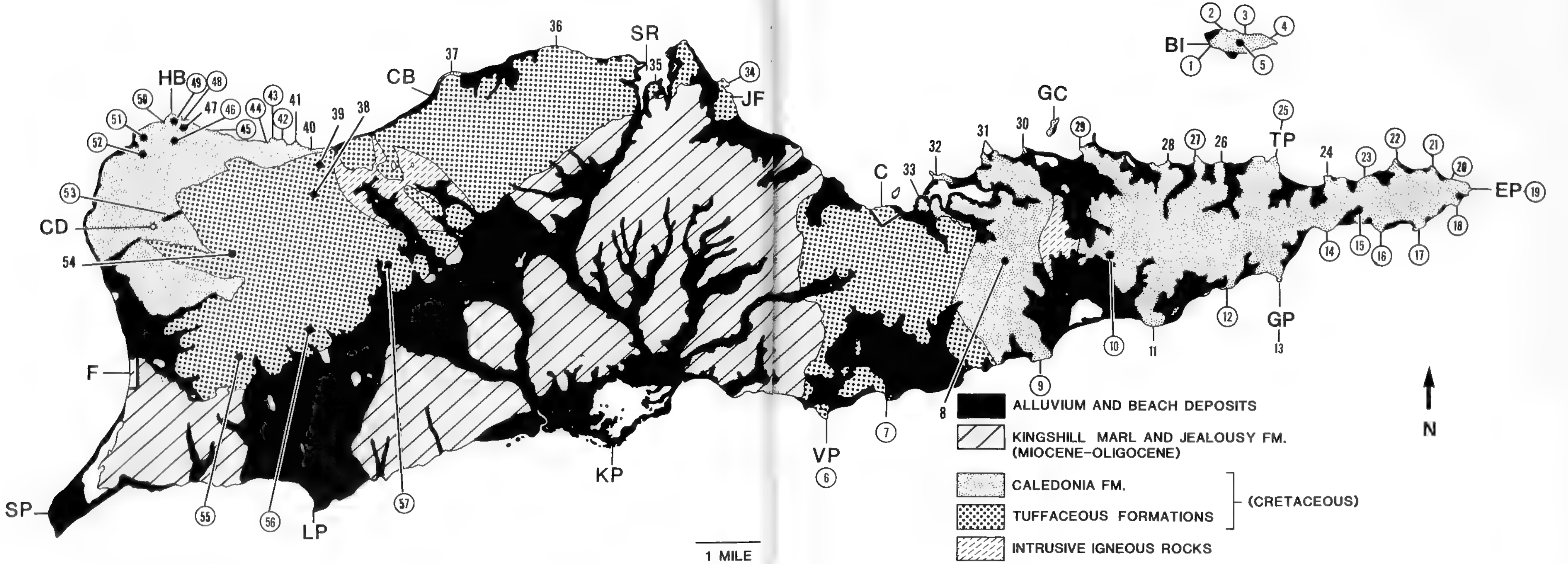


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TABLE 1.—Selected geographic sites (letter code) and localities of upper Upper Cretaceous samples (numerical code) retained in the Smithsonian NMNH-Sedimentology collection. Letter and number codes are shown on geological map in Figure 2 (pages 4 and 5).

Letter Code	Geographic Name
BI	Buck Island
C	Christiansted
CB	Canebay
CD	Creque Dam reservoir
EP	East End Point
F	Frederiksted
GC	Green Cay
GP	Grass Point
HB	Hams Bluff
JF	Judith Fancy
KP	Krause Point
LP	Long Point
SP	Sandy Point
SR	Salt River
TP	Tague Point
VP	Vagthus Point

Number code	Geographic name
1	Buck Island, west sector
2	Buck Island, northwest sector
3	Buck Island, north-central sector
4	Buck Island, northeast sector
5	Buck Island, central, near tower
6	Vagthus Point
7	Manchenil Point
8	Lowrys Hill, road cut
9	Milord Point
10	Hill (512 feet elevation), 1.3 km NNE of Great Salt Pond
11	Mt. Fancy Point
12	Rod Point, west end of Rod Bay
13	Grass Point
14	Grapetree Point
15	Road cut on ridge, above Grapetree Bay
16	Hughes Point
17	Isaac Point
18	Point Cudejarre
19	East End Point
20	Andrea Point, NW of East End Point
21	Lamb Point
22	Cottongarden Point
23	Knight Point, E of Knight Bay
24	Romney Point
25	Tague Point
26	Marys Fancy Point, Yellowcliff Bay
27	Pow Point
28	Coakley Bay Point
29	Chenay Bay, W of Pull Point
30	Punnett Point
31	Shoy Point
32	Radio Tower, Christiansted
33	Mt. Welcome, Christiansted
34	Judith Fancy (Watch Ho)
35	Salt River, Faile property
36	Baron Bluff
37	Canebay, east end of North Star Beach
38	Scenic Road, 1 km E of Mount Stewart
39	Scenic Road, 0.7 km SW of Davis Beach
40	Beach, E of Ellen Point
41	Ellen Point
42	Point, W of Ellen Point
43	Annaly Bay
44	Cobble beach, W of Annaly Bay
45	Adrienne Bay
46	Scenic Road, 0.6 km S of Lighthouse
47	Trail N off Scenic Road, 0.7 km SE of Lighthouse
48	Maroon Hole
49	Road cut near Lighthouse, E of Coast Guard Station
50	Hams Bluff
51	Scenic Road, 0.4 km N of Caledonia Gut quarry
52	Caledonia Gut quarry
53	Creque Dam ravine, above reservoir
54	Road cut between Oxford and Annaly
55	St. Croix Stone and Sand quarry, near St. George Hill
56	Ravine, 1/2 km S of Allandale
57	Springfield Crusher quarry, NW of Grove Place

were examined during these excursions, with a primary focus on the sedimentary attributes of the Caledonia Formation in both eastern and western St. Croix, and on Buck Island. The latter, slightly longer than 1 mile (1.6 km), lies north of the eastern sector of St. Croix (Figure 3).

The Cretaceous exposures on St. Croix occur along the eastern and northwestern ends of the Island (Figure 2). Numerous sections were examined in the East End Range, a hilly (elevation to 866 ft; = 264 m), topographically irregular region approximately 10 miles (16 km) long extending eastward to East End Point (site 19, Figure 2). Localities also were examined in the generally higher Northside Range (elevation to over 1100 ft; = 335 m). This latter physiographic province forms an east-northeast trending belt, approximately 10 miles (16 km) long, extending from the west and northwest coast of St. Croix (Figure 4) to the north-central coast of the island, i.e., to the Estate Judith Fancy (site 34, Figure 2). The two Cretaceous highlands are separated by a low, topographically more gentle area that trends southwest to northeast. This mid-island depression is underlain by Miocene to Recent carbonates and alluvium.

The tectonic complexity of the Cretaceous units is recorded on the geological map of St. Croix and Buck Island prepared by J.T. Whetten in 1961 and subsequently published by the

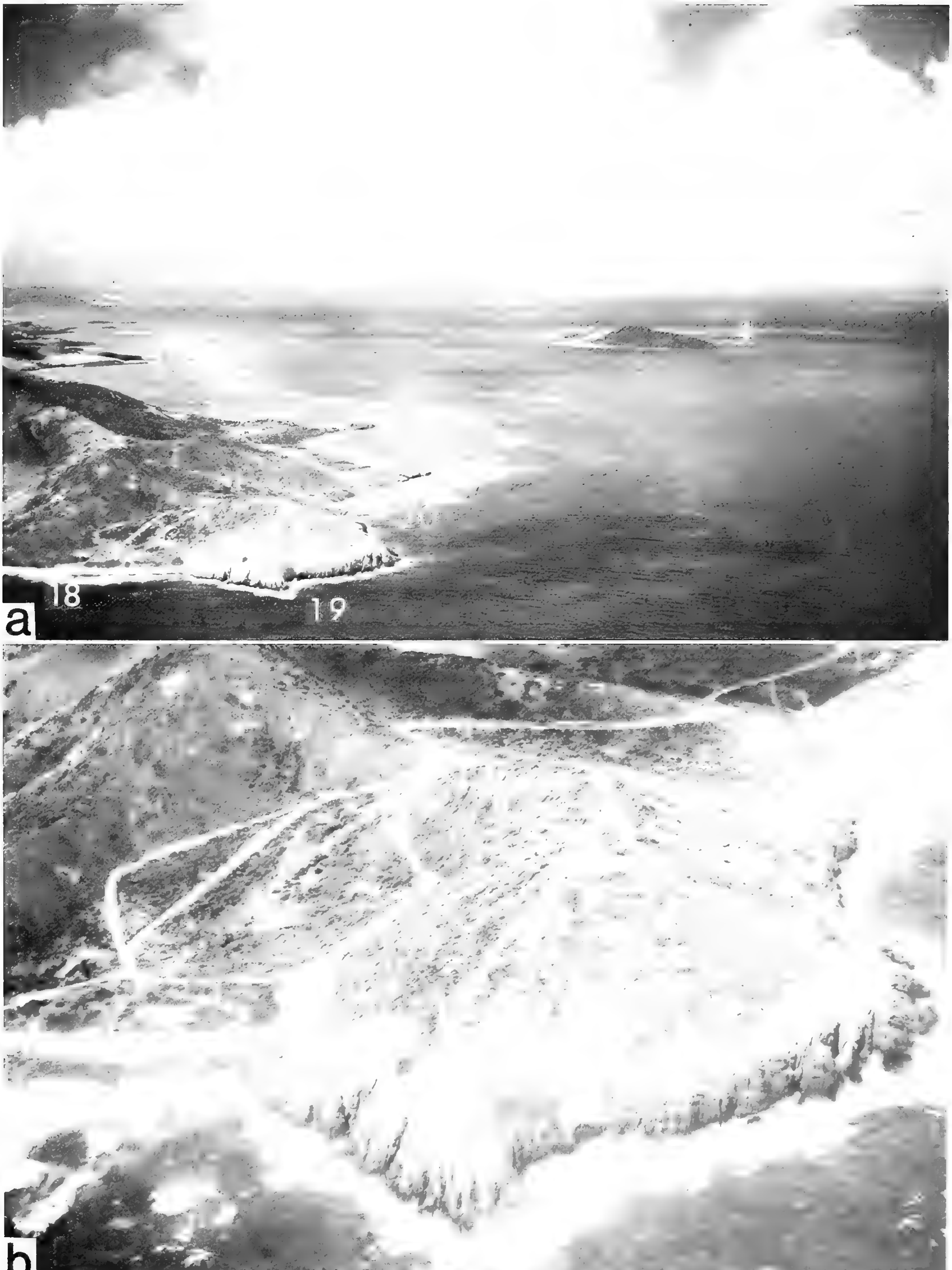

FIGURE 3.—Aerial photographs of eastern St. Croix. *a*, View toward the WNW, showing several study localities: east-northeastern coast of Buck Island (4), Point Cudejarre (18), East End Point (19), Andrea Point (20), Lamb Point (21), Cottongarden Point (22), Knight Point, east of Knight Bay (23), and Tague Point (25). Localities shown in Figure 2. *b*, View toward West, showing near-vertical tilting of Caledonia Formation strata at East End Point (site 19). Photos made from color slides provided by D.K. Hubbard, West Indies Laboratory, St. Croix.

Geological Society of America (1966a). The rocks, for the most part intensely folded, are sometimes tilted to the vertical (Figure 3) and even overturned. Locally, sections of varying thickness have been subjected to further deformation (Figure 4) and, in addition to faulting, have been displaced as thrusts. Moreover, many Cretaceous sections are highly sheared and display the effects of low-grade metamorphism. More locally the rocks in some sections are also considerably modified petrologically by the effects of igneous intrusions. These factors, plus the effects of the generally intense and locally deep weathering (to depths in excess of 5 m), result in poor preservation, thus making it difficult to identify some of the primary sedimentary features, particularly in exposures away from the coast.

It became apparent early in the study that Cretaceous exposures near the coast and in quarries are the ones most useful for thorough sedimentological (including paleocurrent) interpretation in the field. The majority of inland outcrop localities are less suitable. This is due to extensive structural deformation, poor and discontinuous exposure of the Cretaceous rock units, intense tropical weathering, and to the vegetal cover. The best exposures for the identification of sedimentary structures and for recording paleocurrent measurements occur directly at the coast, where rock strata are polished or weathered such that lamination surfaces and other bedding features become emphasized. Most localities are readily accessible, with the exception of the coastal cliff exposures in the extreme northwest sector of the island, i.e., from Hams Bluff eastward to Annaly, which are best reached by boat (Figure 4). There are also several sections within the island away from the coast that provide good exposures for sedimentological examination. Noteworthy are large quarries (sites 52, 55, and 57) and the Caledonia Formation section cropping out in the ravine northeast of Creque Dam reservoir (site 53), all shown in Figure 2. The latter locality was also emphasized in the study by Whetten (1966b).

Exposures of terrigenous and volcaniclastic sections of the Caledonia Formation and of the equivalent and younger Cretaceous units (primarily the Judith Fancy and Cane Valley formations, cf. stratigraphic section depicted in Whetten, 1966b, fig. 3) were examined at about 100 sites on St. Croix and Buck Island. Black and white and color photos of strata were taken at each outcrop locality shown in Figure 2. In addition, notations detailing stratification, sedimentary structures, and metamorphic, volcanic, and structural characteristics were made at these localities. Representative rock samples were collected at 57 of these sites and their locations are shown in Figure 2 (geographic names are listed in Table 1). The numerical field-collection code and outcrop locality name of all samples in the Smithsonian collection are identified in Table 2. The field-collection number of the polished hand specimen and thin sections actually illustrated in this monograph are listed in Table 3. The polished rock slabs and thin sections are presently retained at the Sedimentology Laboratory, Department of Paleobiology of the Natinal Museum of Natural History (NMNH), Smithsonian Institution.

Mineralogical identifications were made in thin section. In the case of heavy minerals where a sufficient number of grains had to be concentrated from highly indurated sandstone, including quartzite samples, it was necessary to first crush the samples and then separate the denser particles in the 62 to 125 µm fraction by using bromoform. Determination of the composition of light and heavy minerals from thin section analysis and examination of heavy liquid separations is often difficult. Identification is hampered by grain alteration resulting from intense weathering or low-grade metamorphism, or usually both. Mineral assemblages are often difficult to identify because of extensive iron staining and the effects of leaching. In several samples the composition of alternating light and dark laminae (which highlight the primary sedimentary structures) were analysed by microprobe. This method revealed that, with respect to chemical composition, the dark laminae are usually iron-enriched in contrast with the light-colored laminae. However, the effects of intense weathering and iron staining have substantially modified original grain surfaces and altered the original composition, and thus probe analysis was only marginally satisfactory for the petrological analyses.

The photographs in this monograph illustrate representative features observed in the field and in polished rock slabs and thin sections. These examples were obtained at 38 of the 57 sample sites shown in Figure 2. Most of the 335 collected rock samples exceed 8 cm in maximum diameter. All have been sliced and polished to reveal features that are generally poorly (and sometimes not at all) visible at the outcrop. About 85 large (to 7 by 10 cm) thin sections on glass were prepared from selected samples to enhance features that in many cases are only vaguely defined even in the polished sections. Photographs of the polished samples and thin sections illustrated in this study are reproduced at a 1:1 scale.

The basal surface of beds is only rarely exposed at most localities. Thus, insofar as paleocurrent measurements are concerned, only a moderate number could be made using base-of-bed or sole structures on sandstone strata, such as groove, cut-and-fill, flame, flute, and load markings. More commonly, apparent current-direction measurements were made using structures within the upper part of sandstone strata, such as foreset, cross-laminated, and climbing-ripple laminations, as well as aligned and imbricated rip-up clasts. Some asymmetrically rippled, upper-bedding surfaces were also useful for paleocurrent measurements. Directional measurements indicating gravity flow and bottom-current transport are listed in Table 2 and separately depicted in Figure 5.

In view of the intensity of deformation, including overturning of strata and the possible allochthonous nature and rotational displacement of some Cretaceous sequences, caution needs to be exercised in the use of these data. Determination of very precise transport directions at any one locality remains

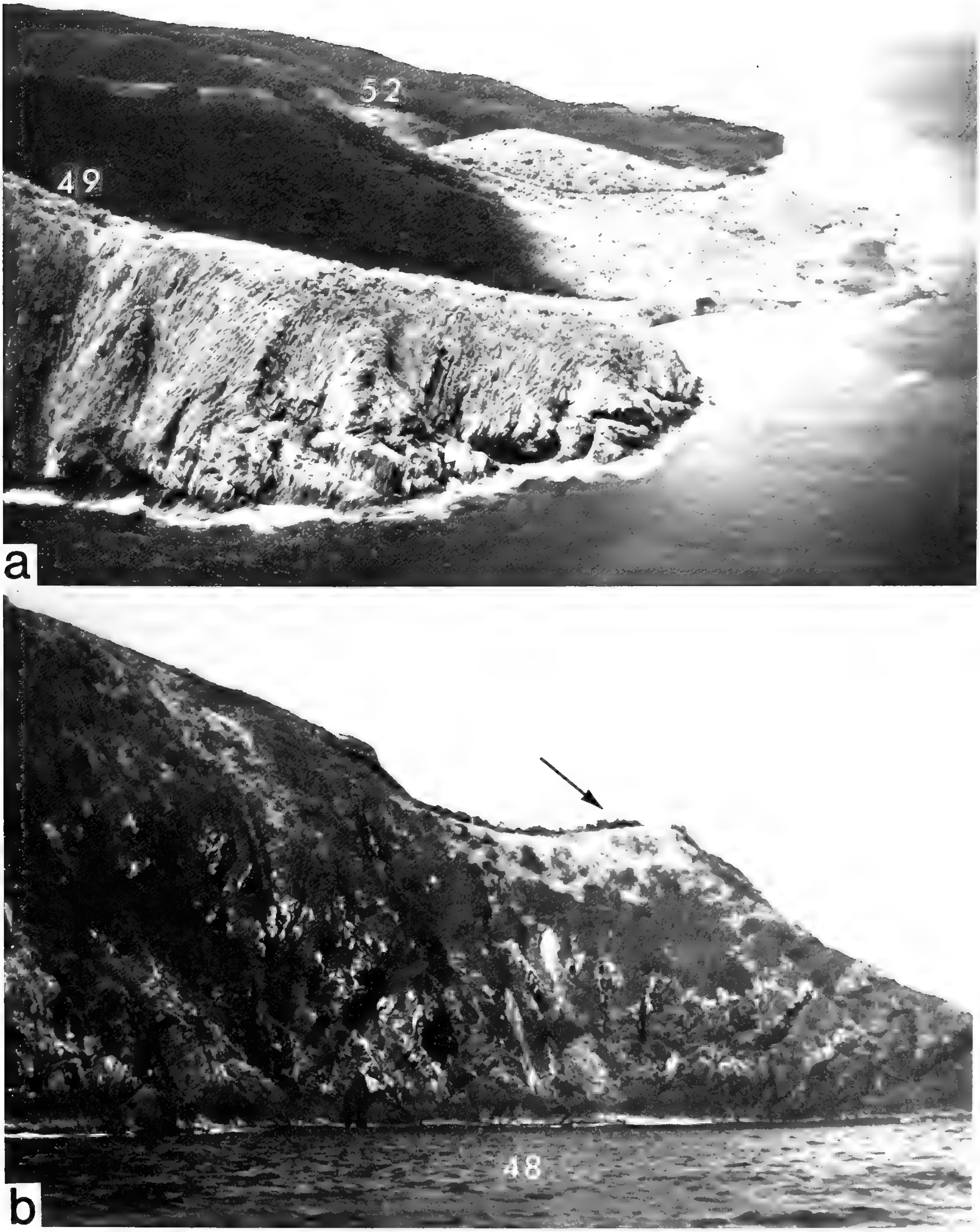

FIGURE 4.—Aerial photographs: *a,* Northwestern corner of St. Croix (view toward SSW), showing several Caledonia Formation study localities: road cut site near lighthouse east of Coast Guard Station (49), Hams Bluff (50) and, in distance, upper part of Caledonia Gut quarry (52). Localities shown in Figure 2. Photo was made from color slide provided by D.K. Hubbard, West Indies Laboratory, St. Croix. *b,* View from sea toward steep cliffs of Caledonia rocks behind Maroon Hole (48) and lighthouse terrace (arrow) above Hams Bluff. Strata are folded, faulted, and intensely sheared. This structural deformation hampers regional stratigraphic correlation and sedimentological interpretations.

TABLE 2.—Cretaceous rock samples collected on St. Croix and Buck Island. Measured paleocurrent directions at selected localities are also recorded.

Sample number code (year-sample number)	Geographic locality name	Locality code (Figure 2)	Prevailing bottom-current direction(s)	Prevailing gravity-flow direction(s)
81-1 to 85-5	East End Point	19	SSE, SE	
81-EE (9 samples)	East End Point	19		
81-6, 81-7	Point Cudejarre	18	ESE, SE, NW	NNW-SSE
81-8	Grass Point	13		
81-9 to 81-12	Cottongarden Point	22	W, NW	NNE-SSW, N-S
81-13 to 81-15	Isaac Point	17		
81-16 to 81-18	Andrea Point	20	W, WSW	
81-19 to 81-21	Lamb Point	21		N-S, NNE-SSW
81-22	Hughes Point	16		
81-23	Caledonia Gut quarry	52		
81-24	Grapetree Point	14		
82-1	Lowrys Hill	8		
82-2 to 82-6	Hams Bluff	50		
82-7 to 82-9	Rod Point	12		
82-10 to 82-12	Mt. Fancy Point	11		
82-13 to 82-16	Punnett Point	30		
82-17 to 82-21	Creque Dam ravine	53		
82-22 to 82-25	Hams Bluff	50		
82-26 to 82-28	Milord Point	9		
82-29	Shoy Point	31		
82-30, 82-31	Chenay Bay (west of Pull Point)	29	W	
82-32, 82-33	Coakley Bay Point	28		
82-34 to 82-38	Knight Point	23		
82-39	Mary's Fancy Point (Yellowcliff Bay)	26		
82-40	Pow Point	27		
82-41, 82-42	Tague Point	25		
82-43, 82-44	Romney Point	24		
83-1	Salt River, Faile property	35		
83-2, 83-3	Radio Tower, Christiansted	32		
83-4	Mt. Welcome, Christiansted	33		
83-5 to 83-10	Pow Point	27		
83-11 to 83-18	Isaac Point	17		
83-19 to 83-24	Springfield Crusher quarry	57		
83-25 to 83-60	Hams Bluff	50		
83-61, 83-62	Baron Bluff	36		
83-63 to 83-70	Judith Fancy Estate	34		
83-71 to 83-75	Buck Island, west sector	1		
83-76 to 83-80	St. Croix Stone and Sand quarry (St. George Hill)	55		
83-81	Ellen Point	41		
83-82 to 83-88	Beach, E of Ellen Point	40		
84-1 to 84-3	Point Cudejarre	18	WNW, ESE, E	SSW
84-4	East End Point	19	ESE	
84-5, 84-6	Isaac Point	17	W	
84-7, 84-8	Buck Island, northwest sector	2	NW	
84-9	Buck Island, north-central sector	3	W, NW	
84-10, 84-11	Buck Island, northeast sector	4	W, SW	
84-12, 84-13	Buck Island, center, near tower	5		
84-14	Road cut near Lighthouse, E of Coast Guard Station	49		

TABLE 2.—Continued.

Sample number code (year-sample number)	Geographic locality name	Locality code (Figure 2)	Prevailing bottom-current direction(s)	Prevailing gravity-flow direction(s)
84-15 to 84-22	Hams Bluff	50		
84-23 to 84-29	East End Point	19	SE, ESE, NW	
84-30	Road cut near Oxford	54		
84-31	Scenic road, 1 km E of Mt. Stewart	38		
84-32	Scenic road, 0.7 km SW of Davis Beach	39		
84-33, 84-34	Trail SE of Lighthouse, off Scenic Road	47		
85-1	Point Cudejarre	18	NW	
85-2 to 85-7	Annaly Bay	43		
85-8 to 85-13	Caledonia Gut quarry	52		
85-14	Scenic Road, S of lighthouse	46		
85-15	Scenic Road, N of Caledonia Gut quarry	47		
85-16, 85-17	Cannebay, east end of North Star Beach	37		
85-18	Hams Bluff	50	WNW	
85-19	East End Point	19	NW, W	
85-20	Creque Dam ravine, above reservoir	53		
86-1	Road cut on ridge, above Grapetree Bay	15		
86-2	Maroon Hole	48	WSW	
86-3	Adrienne Bay	45	NE	SW
86-4	Cobble beach, W of Annaly Bay	44	SW	SE
86-5	Point, W of Ellen Point	42	NW	
86-6, 86-7	Ravine, ½ km S of Allandale	56		
86-8	Hughes Point	16		
86-9 to 86-17	St. Croix Stone and Sand quarry	55	W, E(?)	
86-18 to 86-20	Hill (512 feet elev.), 1.3 km NNE of Great Salt Pond	10		
86-21 to 86-26	Springfield Crusher quarry	57	SW	
86-27 to 86-31	Manchenil Point	7	NW, SSE	SE,SSE
86-32 to 86-47	Vagthus Point (Watch Ho)	6		SSE

questionable, but the number of observations at the different sites are believed to be sufficient to delineate the general regional dispersal paths.

Summary Review of the Pre-Tertiary Geology of St. Croix

The island of St. Croix in the northeastern Caribbean is the largest of the Virgin Islands. It is located about 100 miles (161 km) east-southeast of San Juan, Puerto Rico, and approximately 1000 miles (1610 km) southeast of Key West, Florida (Figure 1). This elongate, east-west trending island is 21 miles (33.6 km) long, has a maximum width of 6 miles (9.7 km), and covers an area of 85 square miles (220 square km). The island is positioned on the St. Croix Ridge (Holcombe, 1979), which is separated from the Puerto Rico-Virgin Islands Platform to the north by an elongate (also east-west oriented), deep (to about 5000 m) depression, the Virgin Islands Trough (also called Virgin Islands Basin). Geographic considerations, including morphology, climate and vegetation, have been discussed in publications by Meyerhoff (1927), Cedarstrom (1950), and Multer and Gerhard (1974). Geological studies by Quin (1907), Kemp (1923), and Cedarstrom (1950) have been updated in the detailed investigation published by Whetten in 1966. The reader is directed to this latter monograph and attached map (1966a, scale of 1:31,680) and to subsequent abbreviated summaries (Whetten, 1968, 1974) for a thorough analysis of the Cretaceous stratigraphy and structure of the distinct rock units forming St. Croix, and for interpretations

TABLE 3.—Sample numbers and localities for the polished rock sections and thin sections in the Smithsonian NMNH-sedimentology collections that are illustrated in this study. Geographic name of locality where each sample was collected is given in Tables 1 and 2.

Figure number	Sample number	Locality code (Figure 2)
7a	83-31	50
7b	83-45	50
7c	83-21	57
7d	83-5	27
10a	81-14	17
10b	85-14	46
10c,d	83-10	27
10e	82-3	50
10f	82-6	50
10g	83-70	34
10h	83-24	57
10i	81-21	14
12a	83-18	17
12b	82-8	12
12c	81-20a	21
12d	81-2b	19
12e,f	81-19b	21
12g	81-19a	21
15a	83-47	50
15b	83-26	50
15c	83-38	50
15d	82-37	23
19b	81-EE	19
20a,b	81-EE	19
21a,b	81-EE	19
22a,b	81-EE	19
23a	83-25	50
23b	84-12	5
23c	82-5	5-0
23d	82-36	23
23e	81-23	52
23f	82-34	23
24a	82-23	50
24b	83-46	50
24c	83-53	50
24d	83-54	50
24e	83-78	55
26a	83-64	34
26b	82-28	9
26c	82-38	23
26d	82-42	25
26e	81-23b	52
30a,b	81-9	22
30c,d	82-19	53
30e	81-13c	17
30f	81-1	19
30g	83-14	17
31a	83-23	57
31b	85-1A	18
31c	83-22	57
31d	83-19	57
31e	83-41	50
35a,b	82-24	50
36a	83-73	1
36b	85-1	1-8
36c	84-17	50
36d	85-11	52
36e	82-26	9
36f	83-25	50
37a	86-40	6
37b	86-41	6
37c	86-39	6
37d	86-36	6
42a,b	81-9	22
42c,d	81-10	22
42e	81-20f	21
42f	83-59	50
42g	84-27	19
43a	86-24	57
43b	86-14	55
43c	86-4c	44
43d	86-7	56
43e	86-9	55
43f	86-26	57
43g	86-18	10
46a	83-28	50
46b	85-12	52
46c	81-17	20
46d	84-2	18
46e	83-51	50
47a	84-1	18
47b	82-4	50
47c	83-50	50
47d	84-8	2
47e	83-58	50
48a,b	81-21d	21
48c	84-22	50
48d	85-20	53
48e,f	81-24a	14
49a	83-77	55
49b	81-22	16
49c	84-15	50
50a	83-80	55
50b	83-40	50
50c	81-20b	21
50d	83-71	1
50e	85-4	43
50f	82-21	53
52a	82-25	50
52b	84-9	3
52c	83-35	50
54a	86-1	15
54b	86-17	55
54c	86-28	7
54d	86-27	7

TABLE 3.—Continued.

Figure number	Sample number	Locality code (Figure 2)
55*b*	81-EE	19
56*a,b*	81-7	18
56*c*	81-6	18
56*d,e*	81-5a	19
56*f*	81-23a	52
57*a*	85-18	50
57*b*	85-2	43
57*c*	83-49	50
57*d*	81-15	17
57*e*	82-22	50
57*f*	81-23c	52
57*g*	84-3	18
58*a*	83-57	50
58*b*	84-14	49
58*c*	83-76	55
58*d*	83-34	50
60*a*	86-10	55
60*b*	86-13	55
60*c*	86-16	55
60*d*	86-5	42
61*a*	83-79	55
61*b*	85-3	43
61*c*	82-5	50
61*d*	82-18	53
61*e*	82-25	50
61*f*	84-6	17

of their mineralogy, petrology, and paleontology.

It is now recognized that St. Croix, Buck Island (positioned 1.5 miles, or 2.4 km, north of its eastern margin), and the submerged contiguous platform, are underlain largely by rock sequences of Upper Cretaceous age. A Late (perhaps latest) Cretaceous age for these rocks is indicated by the fossils (including rudists, corals, foraminifera) of Campanian and Maestrichtian age recovered at several sites (Whetten, 1966b; Speed et al., 1979; Kaufman and Sohl, 1974; and N.F. Sohl, U.S. Geological Survey, 1986, pers. comm.). Cretaceous sequences are locally covered by younger deposits: largely limestones of Miocene and Pliocene age, Quaternary alluvium and beach rock, and offshore reefs. Miocene and younger sediments are exposed primarily in the structurally depressed, somewhat lower-lying Central Valley, which extends from the western part of the island in a north-eastward direction toward Christiansted (Curth et al., 1974; Gerhard et al., 1978). This tectonic low is filled in part by the Kingshill Formation of Miocene age (Figure 2); the depression defines a paleogeographic province termed the Kingshill depositional plain (Gerhard et al., 1978) or the Kingshill Seaway by Multer et al. (1977) and Lidz (1982).

The focus in the present study is on the Upper Cretaceous marine sedimentary and volcanogenic rocks, and primarily the Caledonia Formation. This latter is assigned, at least in part, a Campanian age (Whetten, 1966b, fig. 3; 1974, fig. 2), although it may be somewhat younger. Where the strata are well exposed, this formation appears flysch-like (Figure 6*a*). Fresh surfaces display bluish gray to black mudstones (clayey silts usually altered to slates) that alternate with lighter colored sandstone (generally indurated to quartzite) and conglomerate strata (Figure 6*b*). An island-wide survey shows that the thickness of these Caledonia strata is highly variable, with layers ranging from a few millimeters to several meters, and most commonly 1 to 10 centimeters thick. Fine-grained argillite and slate deposits (originally mud, or mixtures of silt and clay, prior to lithification) comprise more than two-thirds of the formation thickness, while sandstone (fine- to coarse-grade sand) layers account for, at most, about 25 percent. Strata with larger debris of granule to cobble size (diameter rarely in excess of 20 cm) form less than 5 percent of the formation thickness. The sand-shale ratio ranges from 1:10 to as high as 1:1. Prior to compaction and lithification, however, the ratio of sand to mud thickness was usually little more than about 1:10.

Although there were no volcanoes on the seafloor at the site presently occupied by St. Croix, the Cretaceous rocks are, for the most part, volcanogenic. The dominant components of these rocks are of volcanic origin, including epiclastic fragments of keratophyres and spillites, and mineral grains derived from volcanic rocks, with only rare fossil debris. The latter usually occur as fragments embedded within coarse-grade fractions and, in the case of microfossils, as shells, usually poorly preserved and often recrystallized, in the fine-grained layers. Whetten (1966b:186) interpreted the Caledonia Formation as a sequence formed largely of epiclastic volcanic sedimentary rocks, i.e., deposits consisting of material eroded primarily from pre-existing rocks in a volcanic terrain. Interbedded within and at the upper part of the Caledonia Formation are mappable units of tuffaceous sedimentary rocks.

The tuffaceous series within the Caledonia Formation (such as the East End Member) and the associated Upper Cretaceous Allandale, Cane Valley, and Judith Fancy Formations, are variable in lithology. They usually comprise "pyroclastic debris of primary eruptive origin as well as volcanic ash and fragments transported by streams and/or reworked by marine currents, in many cases mixed with minor amounts of epiclastic volcanic materials" (Whetten, 1966b:186). At exposures where they are not intensely weathered the tuffaceous formations sometimes appear greenish (apple green) in color. Associated with tuffaceous formations are lava flows, silicified siltstones and, very locally, limestone strata (most notably at Vagthus Point, locality VP in Figure 2). Although well indicated on Whetten's geological map of St. Croix (1966a), it should be noted that the stratigraphic relationship between these tuffaceous rock units and the Caledonia Formation is often poorly defined in the field. The structural-stratigraphic relationship between formations and members is a complicated one and outside the scope of this investigation.

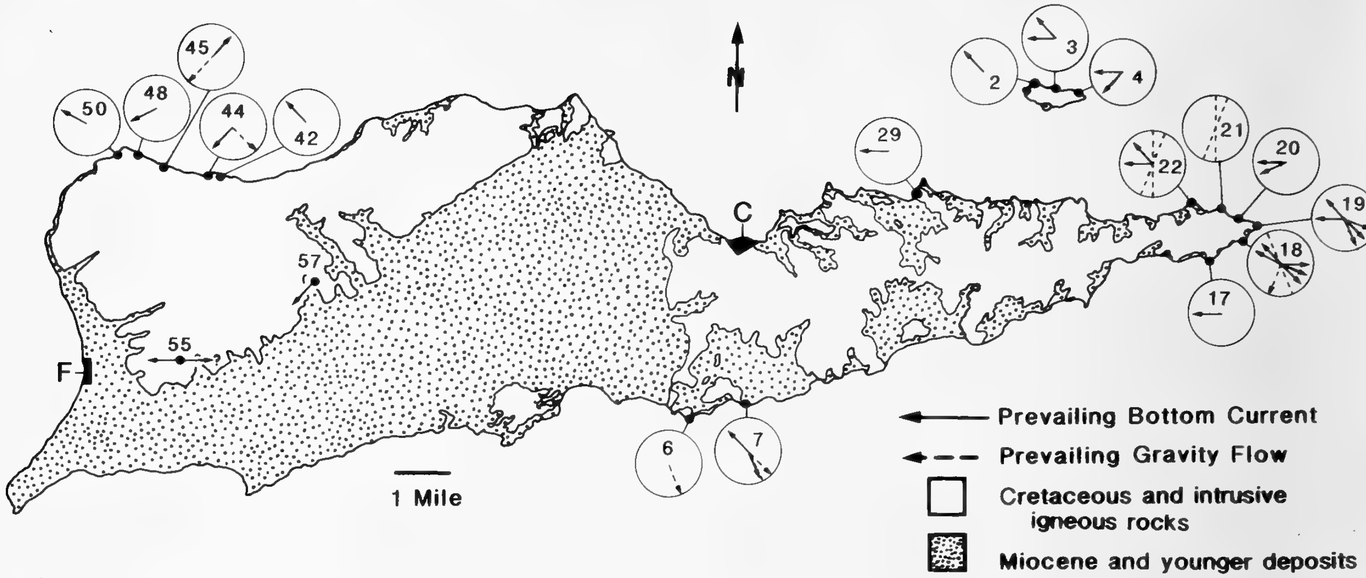

FIGURE 5.—Paleocurrent measurements at 17 selected sites of Cretaceous sequences (primarily Caledonia and Judith Fancy formations) in St. Croix and on Buck Island. At some localities the predominant directions based on structures typical of tractive-current transport diverge markedly from directions measured on structures in sediment gravity-flow deposits. Exposures of Cretaceous rocks shown in white; Tertiary and Quaternary deposits crop out in stippled area (simplified from geological map in Figure 2). Abbreviations: C = Christiansted, F = Frederiksted.

The various above-cited lithofacies on St. Croix are not strictly equivalent with respect to age of emplacement, to petrology, or to depositional environment. *It is emphasized here that, in the present study, sections and samples from the Caledonia Formation and from the tuffaceous series (primarily the Judith Fancy Formation) are selected primarily as examples to illustrate concepts pertaining to sediment transport in general.* The intent is not to formulate a precise paleobasin reconstruction, because it is recognized that the different Cretaceous formations are not strictly co-eval. In particular, isotopic dating would be required in conjunction with field work and drilling on and around St. Croix to obtain a more precise stratigraphic definition of the various Cretaceous units forming the island.

The oldest strata of the Caledonia Formation are believed to crop out on Buck Island (Whetten, 1974:135). Thicknesses of the tuffaceous series and of the Caledonia Formation have been estimated at about 6000 m and 3000 m, respectively. Structural analysis in eastern St. Croix, however, suggests that estimated thicknesses of the Caledonia are probably excessive, since they are based in part on the assumption of a continuous homoclinal structure between Buck Island and East End Point (Figure 3). On the basis of the structural complexity recorded on St. Croix proper (tight folds, faults, thrusts), a stratigraphic continuity of this type can reasonably be questioned.

Tectonic complexities have been recorded wherever Cretaceous rocks crop out and these are depicted on the geological map prepared by Whetten (1966). More detailed geometric analyses of local deformation structures in St. Croix have been presented by Speed (1974) and Speed et al. (1979). The structure of specific areas including Grass Point, Isaac Point, and Green Cay (localities GP, 17, and GC in Figure 2) has been recognized, respectively, by Cohen et al. (1974), Loftsgaarden et al. (1974), and Ratte (1974). In addition to intense shearing and cleavage, folding and faulting, my surveys suggest that allochthonous displacement, including thrusts, in both eastern and western parts of the island is probably even more important than indicated in these earlier studies.

Focusing on the eastern part of St. Croix, Speed (1974) and Speed et al. (1979) indicate that structural deformation and volcanism occurred during, or shortly after, deposition of the sediments in the Late Cretaceous. The deformation, as exemplified by the rocks in the eastern part of the island, is the probable result of strong impulsive, but short-lived, activity that affected the whole of the Greater Antilles (Speed et al., 1979). This is recorded at the outcrop by syndepositional modification, including the almost ubiquitous, deformed, sedimentary structures, several examples of which are illustrated in later sections of this monograph.

Attention has been called to the small bodies of igneous rocks that intruded the Cretaceous rocks. Some of these intrusions, mapped by Whetten (1966a), are shown in Figure 2. Sedimentary rocks adjacent to such igneous bodies are usually intensely modified, and the sedimentary and other primary structures appear indistinct at the outcrop or are obliterated. According to Speed et al. (1979, table 1) such dikes

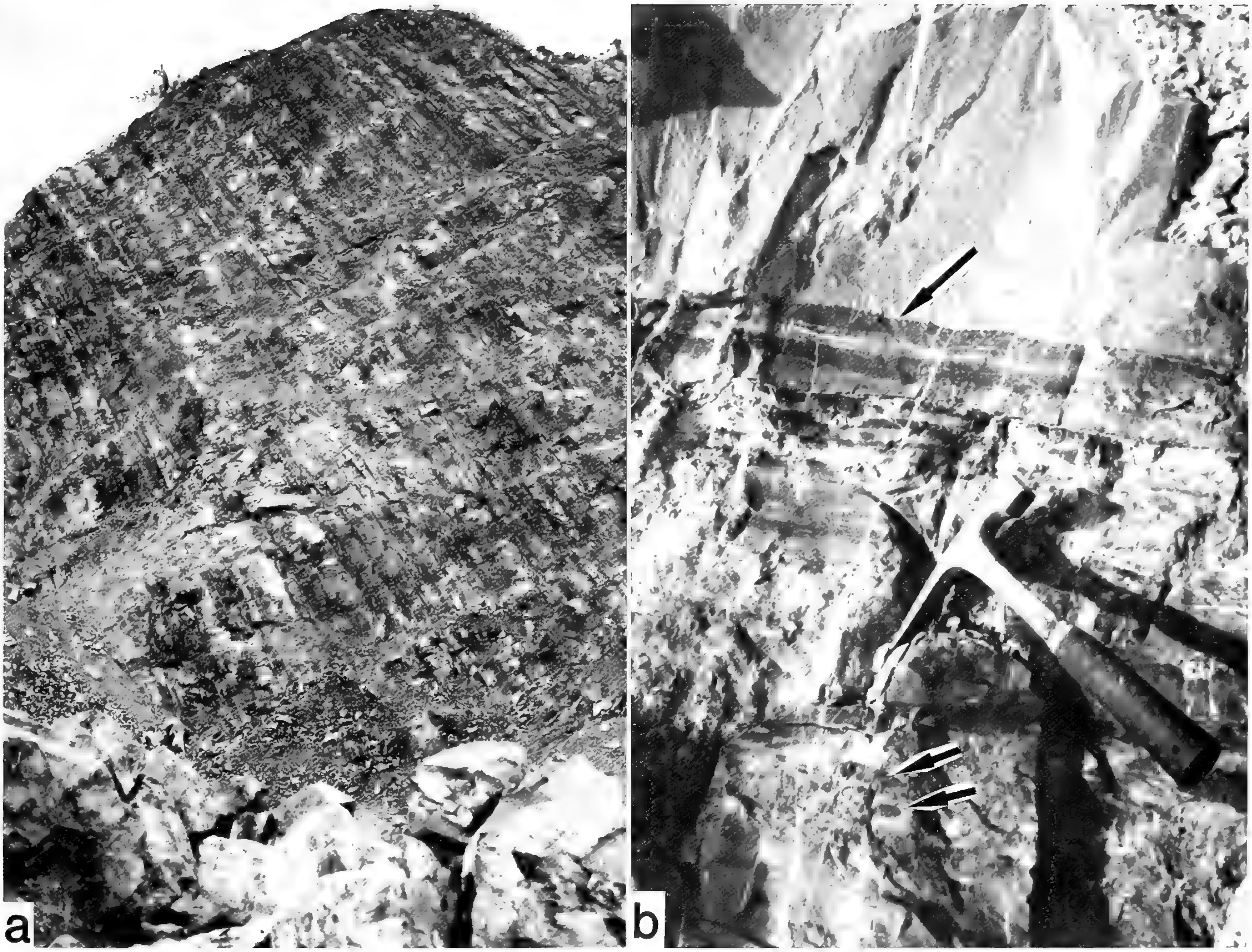

FIGURE 6.—Photographs at Springfield Crusher quarry (site 57, Figure 2). *a*, Steeply dipping flysch-like Caledonia series of alternating quartzite and slate strata; section shown is about 70 m thick. *b*, Fresh quarry surface, exposing unweathered lower part of thick (about 1 m) sandstone turbidite; note sharp contact (single upper arrow) between turbidite base and underlying fine-grained (slate) deposit. Two elongate imbricated rip-up mud clasts (lower two arrows) in an underlying sandstone layer indicate transport from right to left; hammer (28 cm long) provides scale.

and at least one pluton were emplaced between 74 and 64 million years ago, quite probably the product of regionally intense plutonism during the Maestrichtian.

A recent review article on the regional geological evolution of the Caribbean by Case et al. (1984) alludes in a general way to the Mesozoic and Tertiary history of the Virgin Islands and Puerto Rico relative to that of other islands in the region. That study and those by Pindell and Dewey (1982), Burke et al. (1984, fig. 48), and Mattson (1984, figs. 4 and 5) indicate that the Caribbean ocean floor shifted to the northeast, and then to the east, between Mexico and South America, during the Late Cretaceous. In recent years authors have invoked motion along major transform structures (Vila et al., 1986) and active underthrusting of the Caribbean plate beneath South America during this period. The specific mechanisms that led to this structural evolution and resulted in the present island-arc configuration are still under discussion. It is quite clear, however, that the rocks of Late Cretaceous to Eocene age exposed on islands in this part of the Caribbean record the effects of particularly intense tectonic deformation and volcanism that molded the region.

Sedimentary Evidence for Downslope Transport

BASE-OF-SLOPE DEPOSITIONAL SETTINGS.—Field observations made during the course of this study substantiate the

conclusion that the volcaniclastic deposits forming the Cretaceous rocks on St. Croix were transported on slopes, probably in an active tectonic arc setting (Whetten, 1966b, 1974). Perhaps these slopes were the margins bounding an island-arc front basin or trench, or alternatively, constituted base-of-slope settings between the arc and back-arc basin, as suggested by Speed (1974). The present petrologic study indicates that these gradients, in either case, were in proximity to zones of active volcanic activity, both intrusive and extrusive. Not only was sediment accumulation penecontemporaneous with volcanism, but the layered deposits were structurally deformed (Figure 4) during and shortly after their accumulation.

It would appear that both the Caledonia volcaniclastics and the somewhat younger tuffaceous deposits (Judith Fancy and other) were transported on slopes. A base-of-slope setting is interpreted on the basis of the assemblages of gravity-driven mass flow sediments types, the most significant including slides, slumps, and coarse-grained, sediment gravity-flow deposits (definitions in Middleton and Hampton, 1973:1–31). These latter include debris-flow and sand-flow (including grain-flow) units (cf. Stanley et al., 1978:106–109), as well as coarse-grained turbidites. Although very important for interpreting environments, the above-cited sediment types, together, account for less than 10% of the total thickness of the Cretaceous section. It is difficult to quantify slope gradient, but the transport for any distance of the deposits cited above (particularly the non-graded or poorly graded sand flow/grain flow deposits, Figure 7) may require slopes of at least 5 degrees. This is a conservative estimate and, locally, steeper gradients are suggested. Examples of high-gradient settings include the walls of slope channels (to >10°), the configuration of which are recognized on the basis of the geometry of strata sequences.

A distal setting has been suggested for the Cretaceous deposits on St. Croix by earlier workers: i.e., environments beyond the toe of a subsea fan (Speed, 1974:193), or somewhat more distal environments on the margins of a basin (Speed et al., 1979:631). In my view, the distinctive association of mass-flow deposits cited in this text indicates a more proximal setting, more likely a slope apron rather than a fan lobe.

Slides, Slumps, and Debris-Flow Deposits.—A significant component of the downslope-directed mass flows consists of gravity slides, where large slabs of strata have moved with only slight internal deformation as the allochthonous masses moved basinward on one, or a few, well-defined slippage planes. Identification of slides is most reliable in outcrop sections that are sufficiently large and well-exposed, and where stratification surfaces can be traced laterally. Several examples can be observed (e.g., Caledonia Gut quarry; site 52, Figure 2). In contrast with slides, slumps involve displaced packets of strata that reveal extensive internal deformation. The term is also applied loosely herein to a large sediment mass, usually sandstone or mudstone or both, that has become detached as an allochthonous packet during transport, and is incorporated on or within another layer. Slumps are usually of geometrically smaller scale than slides and thus are more readily identified at the outcrop. Well-exposed examples of slumps include those of the Judith Fancy Formation at the Estate Judith Fancy locality and illustrated by Whetten (1966b, pl. 6).

Some conglomerates found in the different Cretaceous sequences are identified as subaqueous debris-flow deposits. This interpretation is made in those cases where it is surmized that large clasts are displaced by processes involving matrix-support. In this transport mode, the larger particles are borne by moderately concentrated to dense mixtures of sand, mud, and water (cf. Hampton, 1972; Middleton and Hampton, 1973, fig. 10). Various types of conglomerate-rich debris-flow deposits, or "debrites," occur in both the eastern and western sectors of St. Croix and on Buck Island, where matrix-supported (Figure 8), partially grain-supported (Figure 9*a*), and grain-supported (Figure 9*b*) types are recognized. The clasts, "floating" in matrix of sand or mud or mixture of both, commonly include a diverse polygenic mix (Figure 10) of epiclastic fragments of keratophyres and spillites, quartz, and other lithologies identified by Whetten (1966b). At several localities, conglomerates consist essentially of angular and subangular debris of fairly homogenous igneous lithology. Although transport-wise, these are sedimentary in origin, they resemble deposits of volcanic flow (lahar) units (Figure 11*a*). The larger grains are usually embedded in a volcaniclastic matrix (Figure 12*a*). In the case of finer-grained debris flows, a diversity of grain sizes, mineral types, and fabric structures are identified in thin section (Figures 10*i*, 12*b,d,f,g*). Pebbles in "debrites" may display a coherently organized configuration, and examples include graded (Figures 13, 14*b*) and stratified (Figure 11*a*) layers. In more than two-thirds of the observed cases, however, particles are dispersed randomly and appear as disorganized masses (Figure 9*a*).

Clasts with a diameter larger than 100 centimeters have been measured, but in most conglomerates the clast diameter is usually less than 10 centimeters. Gravity emplaced deposits, where coarse sand- and granule-size particles are embedded in a matrix of fine-grained sand and finer material (Figures 10, 12*c–g*), are not uncommon. In shape, lithic clasts range from angular (some in Figure 10*c–e*) to well rounded (Figure 8*a*), but most are subangular to subrounded (Figures 9*a*, 10*a*). Rip-up clasts of sandstone (quartzite) and mudstone (slate) are most commonly observed in sandstone and conglomerate layers (Figures 6*b*, 9*c*, 10*e*, 13, 15*a,c,d*), and occasionally in siltstone (Figure 15*b*) and mudstone. In some layers elongate particles (lithic fragments and also rip-up clasts) are preferentially oriented with respect to transport direction, i.e., the long axis of elongate clasts may be parallel (Figure 11*b*) or perpendicular (Figure 13) to flow path. Flattened elongate clasts are commonly imbricated (Figures 6*b*, 13, 15*a*, 16), and thus serve as paleocurrent indicators.

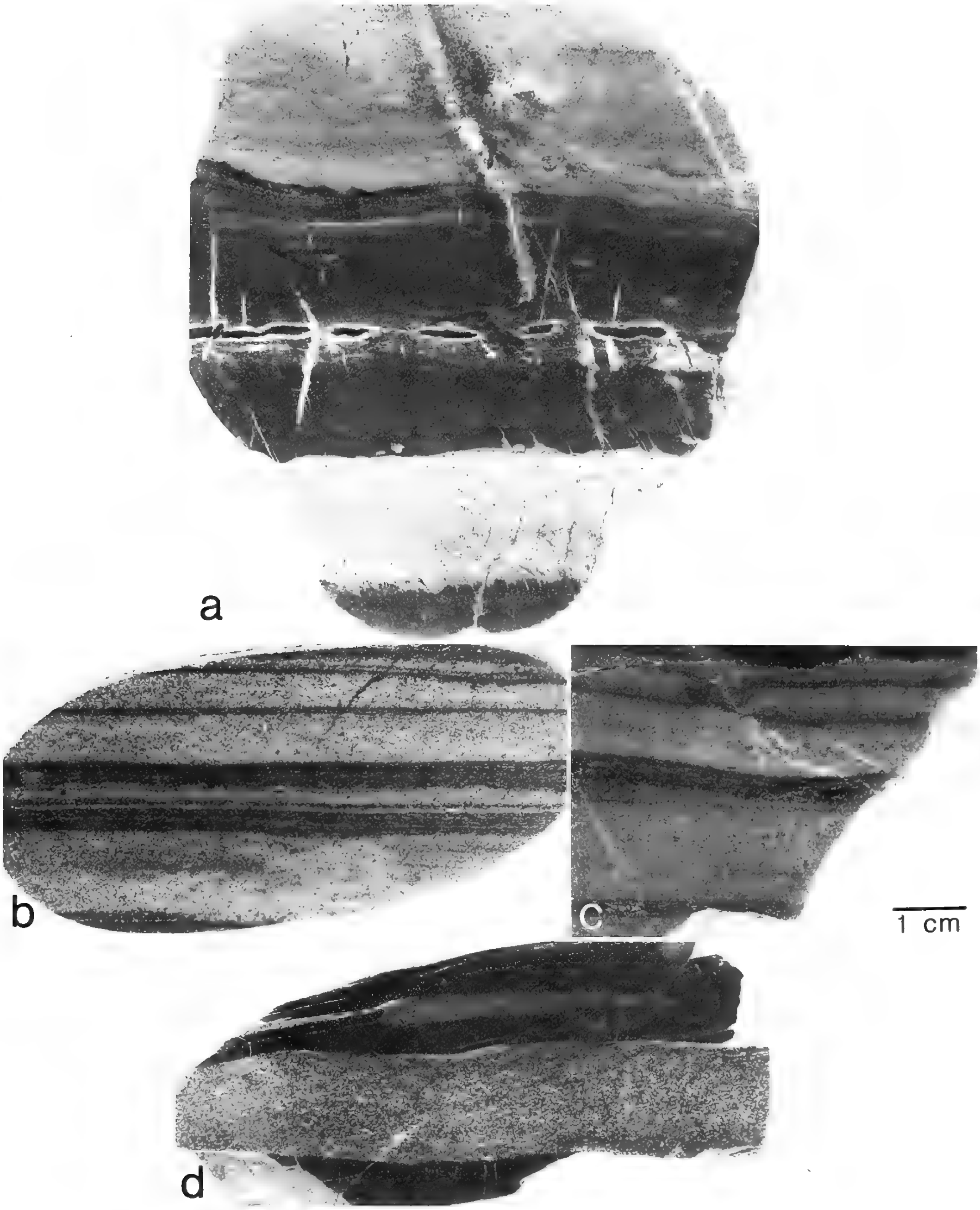

FIGURE 7.— Polished sections of almost structureless, sandy, volcaniclastic layers with sharp top and sharp base. These are interpreted as sand-flow (grain- or fluidized-flow) deposits. Lower sandstone layer in *a*, subtly graded, is similar to basal division A of turbidites. Localities (in Figure 2): *a,b* = site 50; *c* = site 57; *d* = site 27. Scale bar applies to all components.

SHALLOW-WATER COMPONENTS IN SOME MASS-FLOW DEPOSITS.—Of particular interest with respect to possible environmental setting is the well-exposed section of mass-flow deposits (Judith Fancy Formation) at Vagthus Point (also called Watch Ho; site 6, Figure 2) on the southern coast of St. Croix. This locality, mapped as one of the youngest Cretaceous sections on the island (cf. Whetten, 1966b, pl. 7), includes a series of carbonate-rich strata tilted to the near-vertical (Figure 14*a*). The sequence includes numerous thin (1–10 cm), fine-grained, tuffaceous, mudstone and limestone layers (some graded) alternating with thicker (1.0–1.5 m) and much coarser debris-flow deposits; the latter usually comprise large clasts (diameter exceeding 20 cm). Some of the coarse layers display graded bedding (Figures 13, 14*b*). These latter are formed of

FIGURE 8.—Matrix-supported debris-flow deposits with rounded pebbles in sandstone (*a*) and muddy sandstone (*b*). Localities (in Figure 2): *a* = site 7; *b* = site 48. Hammer is 28 cm long.

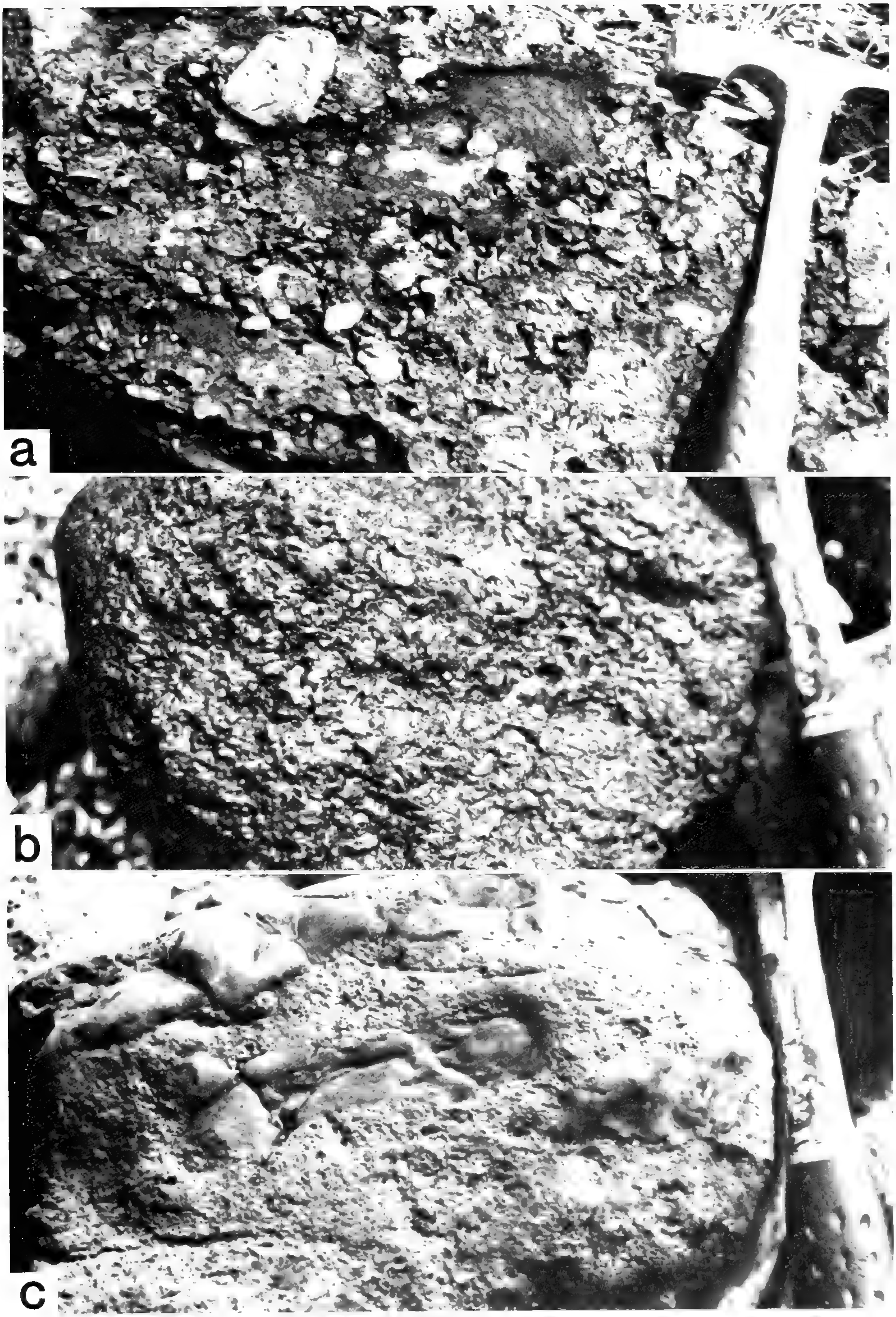

FIGURE 9.—Examples of "disorganized," sandy, debris-flow deposits. *a*, Subrounded volcanogenic clasts, partially matrix-supported; *b*, Clasts, in large part grain-supported; *c*, Siltstone rip-up clasts of various shape concentrated in coarse sandstone. Localities (in Figure 2): *a* = site 7;*b,c* = site 50. Hammer is 28 cm long.

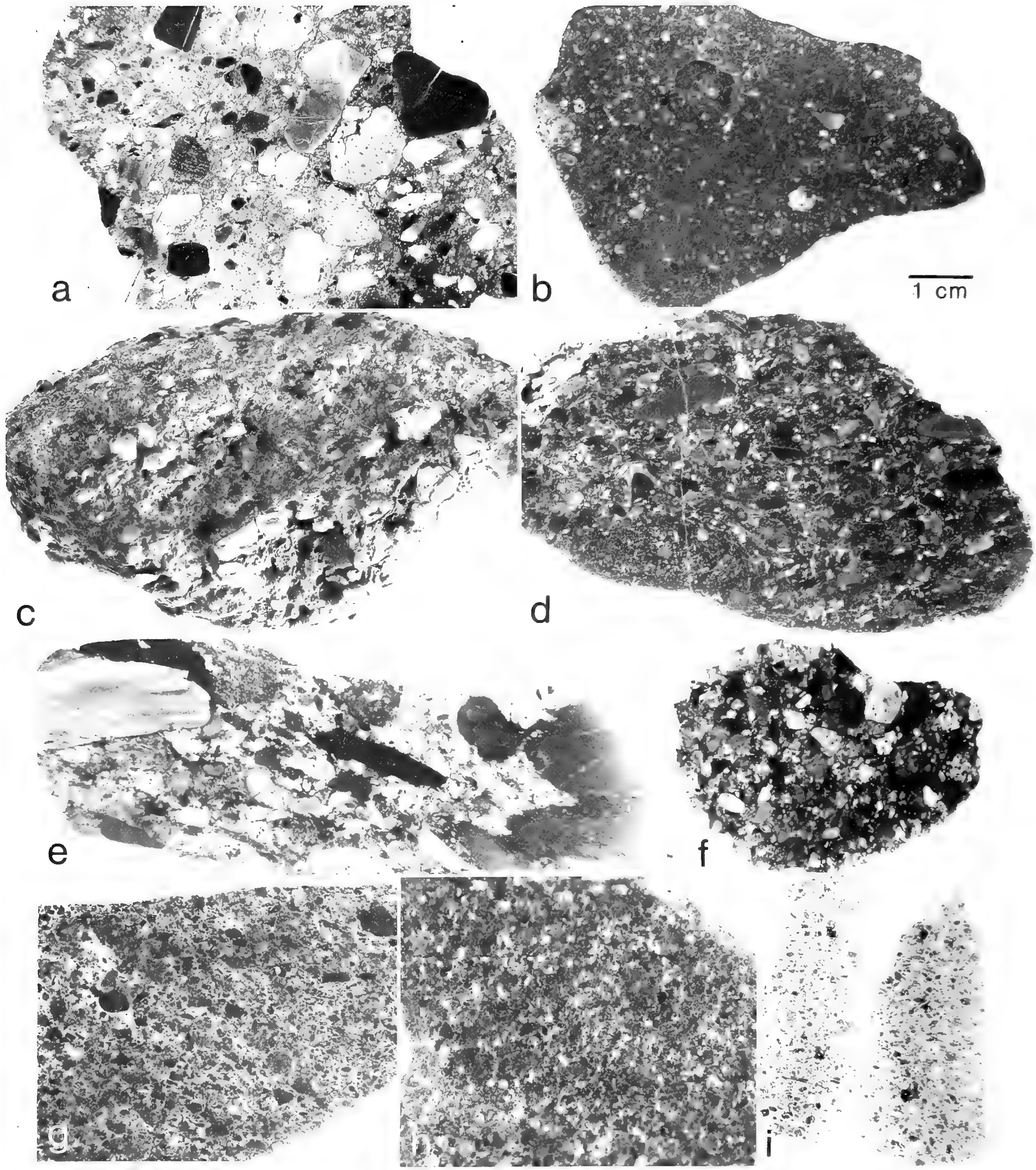

FIGURE 10.—Hand specimen (*c*), polished sections (*a,b,d–h*) and thin section (*i*) of different debris flow deposits (mostly volcaniclastics) showing diverse examples of clast size and shape and clast-to-matrix fabric. For example, some clasts tend to be angular in *c, d,* and *e* and subangular to subrounded in *a,f,* and *g*. Clasts appear to "float" in muddy sand matrix in *b*; in contrast, clasts are in contact with each other in *f*. Localities (in Figure 2): *a* = site 17; *b* = site 46; *c,d* (respectively, hand and polished section of same sample) = site 27; *e,f* = site 50; *g* = site 34; *h* = site 57; *i* = site 14. Scale bar applies to all components.

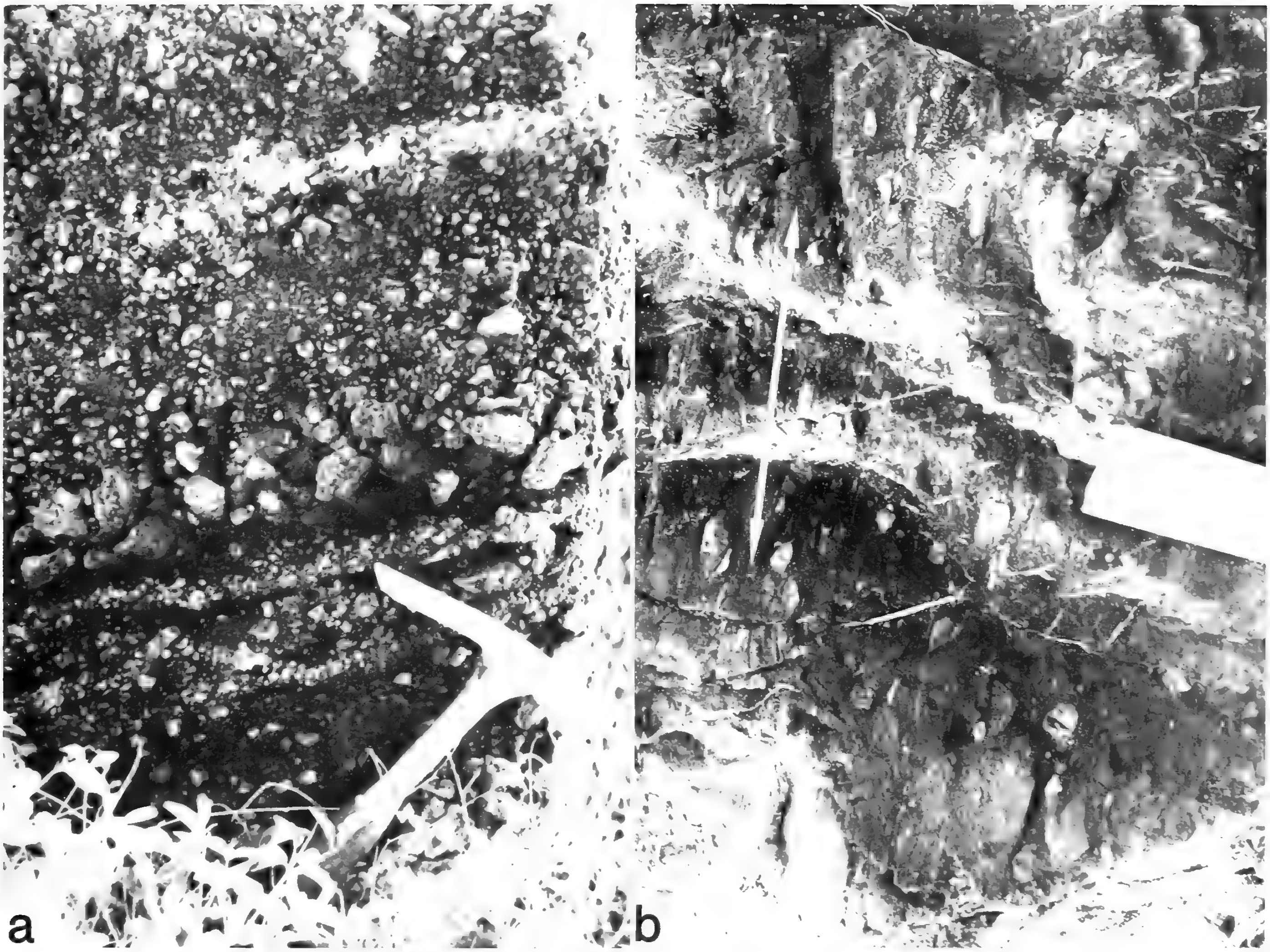

FIGURE 11.—a, Stratified volcaniclastic conglomerate with subrounded to angular clasts, probably submarine lahar-type flow deposit; hammer is 28 cm long. *b,* Base of bed showing alinement of elongate pebbles, with long axis oriented roughly parallel to flow direction (double headed arrow); direction of transport current not defined by pebbles, but by other sedimentary structures such as foreset lamination within bed; book on right is 13 cm wide. Localities (in Figure 2): *a* = site 17; *b* = east of site 1.

detrital limestone and volcaniclastic clasts and a sandy to muddy carbonate matrix, and incorporate complete but worn (Figure 17) or broken rudists and coral fragments (identification in Whetten, 1966b:209–210; Sohl, 1976:31.4). The imbricated orientation of some elongate clasts and the horizontal (flat-lying) position of rounded rudists (such as *Barrettia gigas;* Norman Sohl, 1986, pers. comm.) at the base of some coarse layers (Figure 13) suggest emplacement by high-energy, downslope-directed flows, with probable transport of larger fragments by rolling along the bottom.

The assemblage of detrital biogenic material of neritic or shallower origin, mixed with terrigenous particles in the coarser beds at Vagthus Point, strongly suggests a process involving offshelf spill-over, i.e., transport of biogenic-rich debris from a largely carbonate bank onto a fairly steep slope. The rather consistent thickness of strata, the moderate to well-developed graded bedding, and the preferential orientation and imbrication of clasts at this locality suggest that transport (a) involved downslope-directed, sediment gravity-flow mechanisms and (b) that these flows entrained sediment downslope for a sufficient distance to result in a coherent organization of particles during deposition and the "freezing" of sediment as laterally continuous and well-stratified strata. The Vagthus Point sequence resembles the sequences of mixed, coarse, carbonate debris and finer-layered, calcareous muds on the present-day lower slope off northern St. Croix. These deposits, as observed from the submersible DSRV ALVIN, were derived from the narrow platform and upper slope in

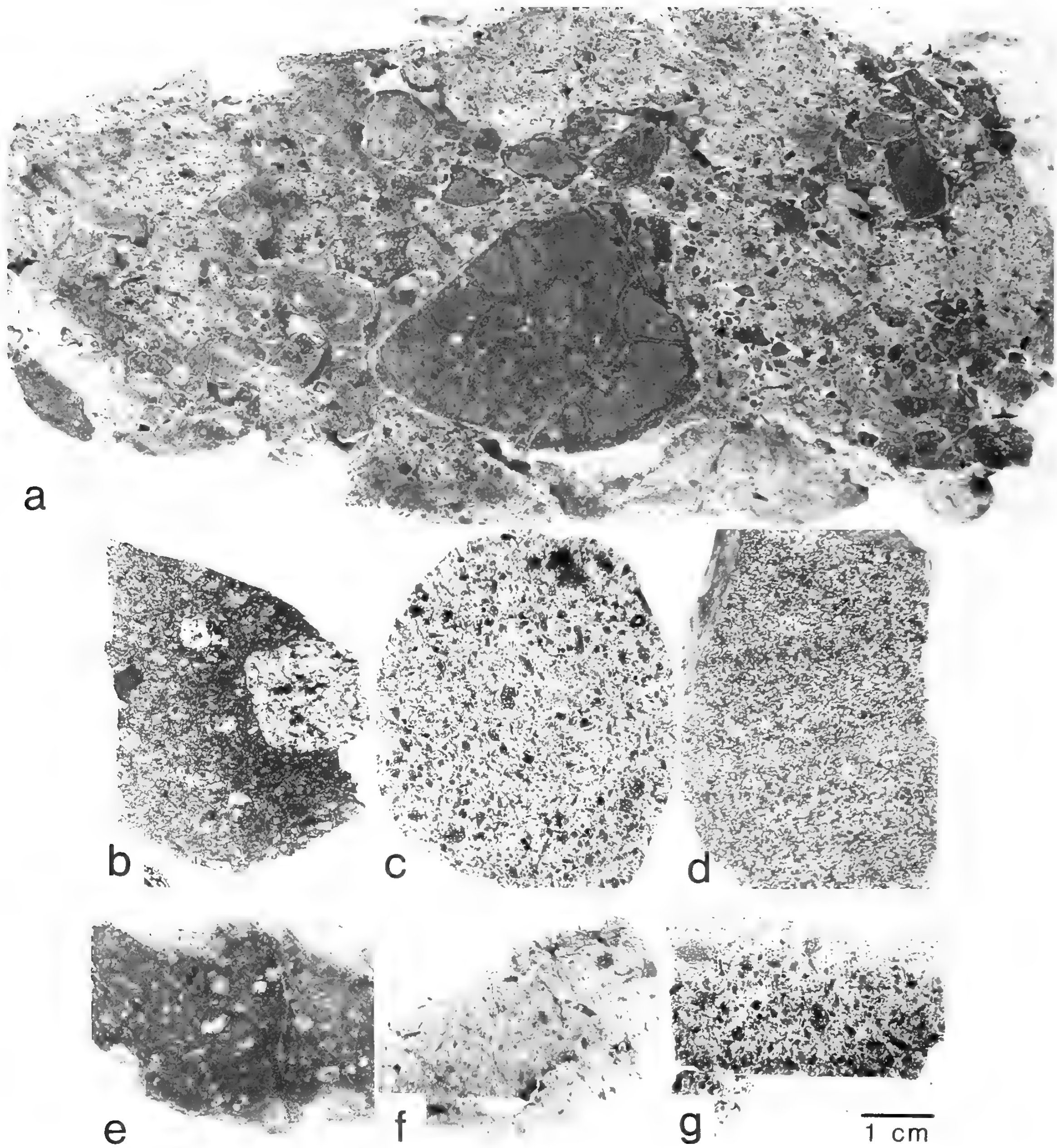

FIGURE 12.—Polished slab (*a,d,e*) and thin sections (*b,c,f,g*) of various submarine volcaniclastic flows. Hand specimen (*a*) was collected at the exposure shown in Figure 11*a*. Samples show disorganized (*b*), to partially organized (*c*), to organized (graded bedding in *d*) nature. Localities (in FIGURE 2): *a* = site 17; *b* = site 12; *c* = site 21; *d* = site 19; *e–g* = site 21. Scale bar applies to all components.

geologically recent (Quaternary) time (Hubbard et al., 1982).

SEDIMENT FAILURE AND DEFORMED STRUCTURES IN SLOPE DEPOSITS.—Further evidence, albeit indirect, of transport processes likely to occur on slopes is recorded by deformed sedimentary structures such as convoluted laminations so commonly mapped in sediment gravity flow deposits at many localities. These convolutions suggest that metastable-collapsible phenomena related to failure occurred during, or shortly after, deposition. Moreover, the structures indicate disruption of the original grain-to-grain fabric, some associated with spontaneous liquefaction and dewatering phenomena. Deformation may be restricted to a localized part of a single layer (Figure 18*b*), or may affect the entire stratum (Figures 19–22). Sometimes several layers are deformed in a parallel manner (Figure 18*a*) or a set of laminae show evidence of syndepositional disruption (Figure 23*b*). The disruption of grain-to-grain contact, as indicated by the destruction of the overall sediment structure and fabric and the expulsion of water

FIGURE 13—Coarse, thick (about 1 m) graded, matrix-supported conglomerate with imbricated pebbles (dashed lines along major axes; several below arrow and left of hammer handle) showing transport from right to left. Light-colored fragment at right base of hammer (28 cm long) is a worn rudist; long axis is horizontal and oriented perpendicularly to imbricated pebbles. Smaller dark pebbles are rip-up clasts of siltstone. Locality is Vagthus Point (Judith Fancy Formation, site 6, Figure 2).

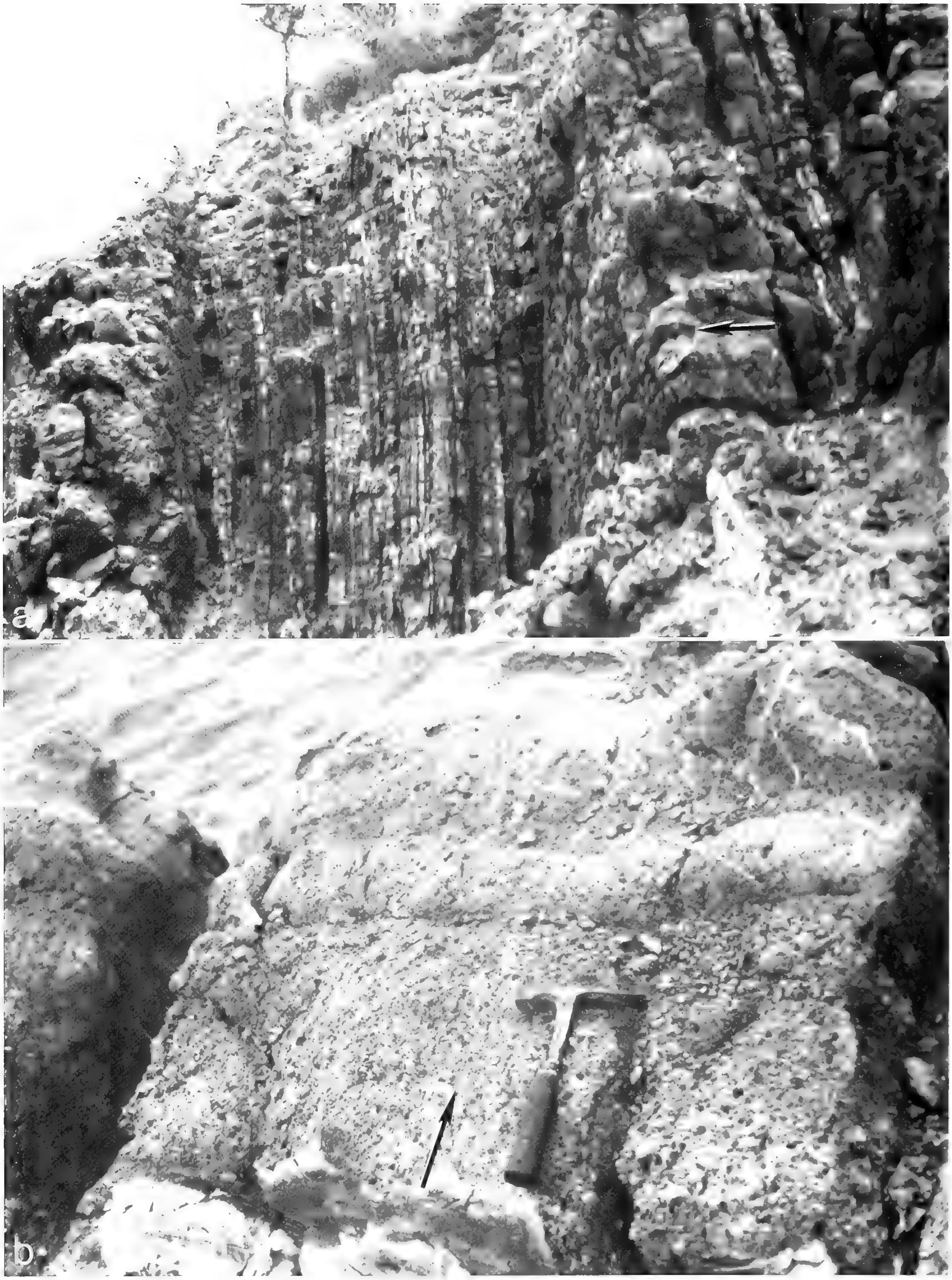

FIGURE 14.—Strata at Vagthus Point (Judith Fancy Formation, site 6, Figure 2), tilted to vertical. *a*, Sequence of thin, coarse, sand- and granule-rich turbidites alternating with thicker (1–2 m) and much coarser debris-flow deposits. Strata comprised of limestone and volcaniclastic components. Arrow shows top of "debrite" toward left. *b*, Close-up photograph of coarse graded stratum; fining upward shown by arrow. Layer contains numerous carbonate, including fossil, fragments. Note erosional pebble-rich base cut into underlying sandstone layer. Hammer is 28 cm long.

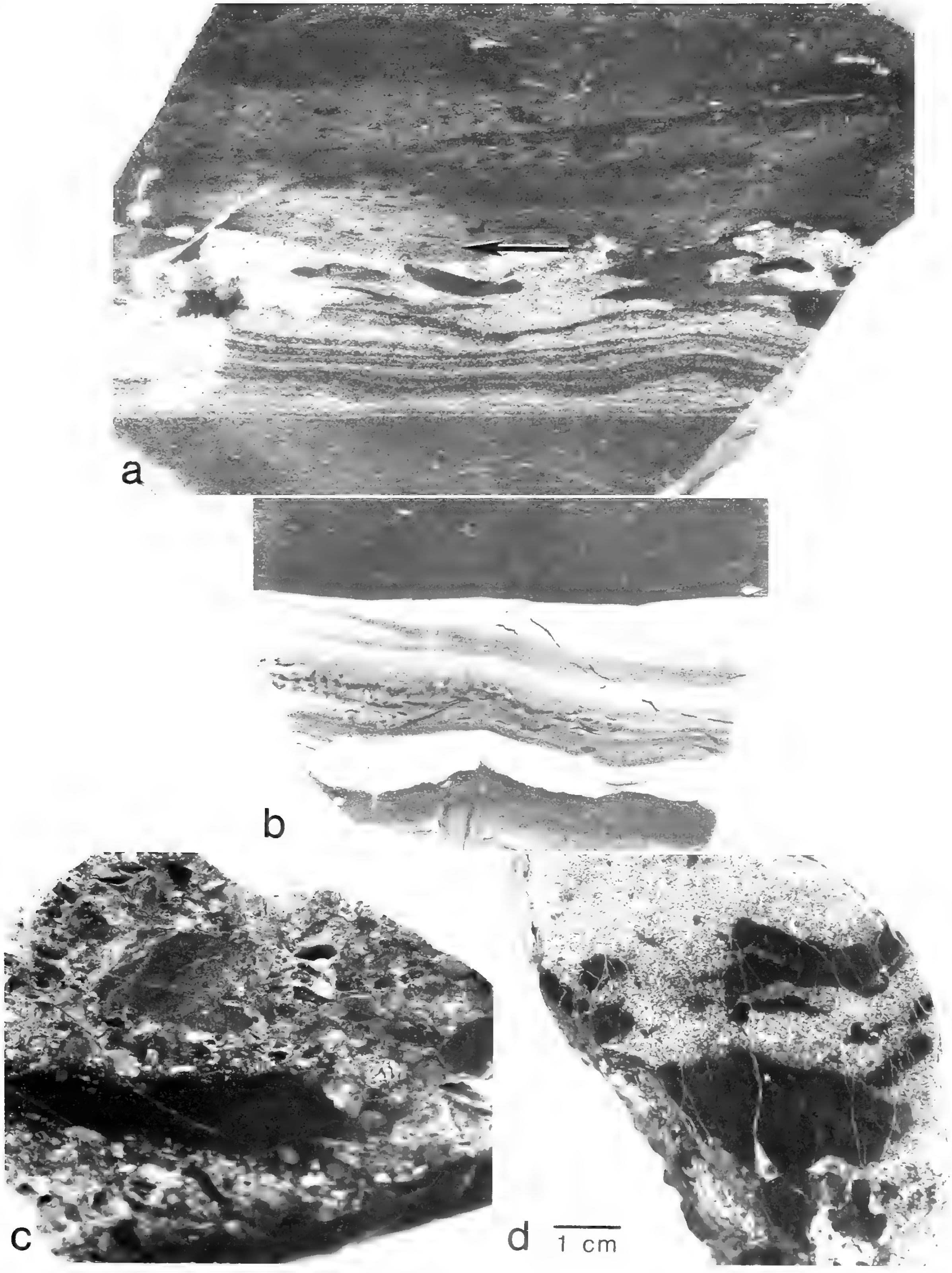

FIGURE 15.—Polished sections showing dark, mudstone rip-up clasts in medium- and fine-grained sandstone (*a,b*), and in coarse-grained sandstone (*c,d*). Angular fragments may be irregularly distributed (*c,d*) or concentrated along specific parts of layers (*a,b*). Elongate clasts sometimes imbricated (transport toward left in *a*). Localities (in Figure 2): *a–c* = site 50; *d* = site 23. Scale bar applies to all components.

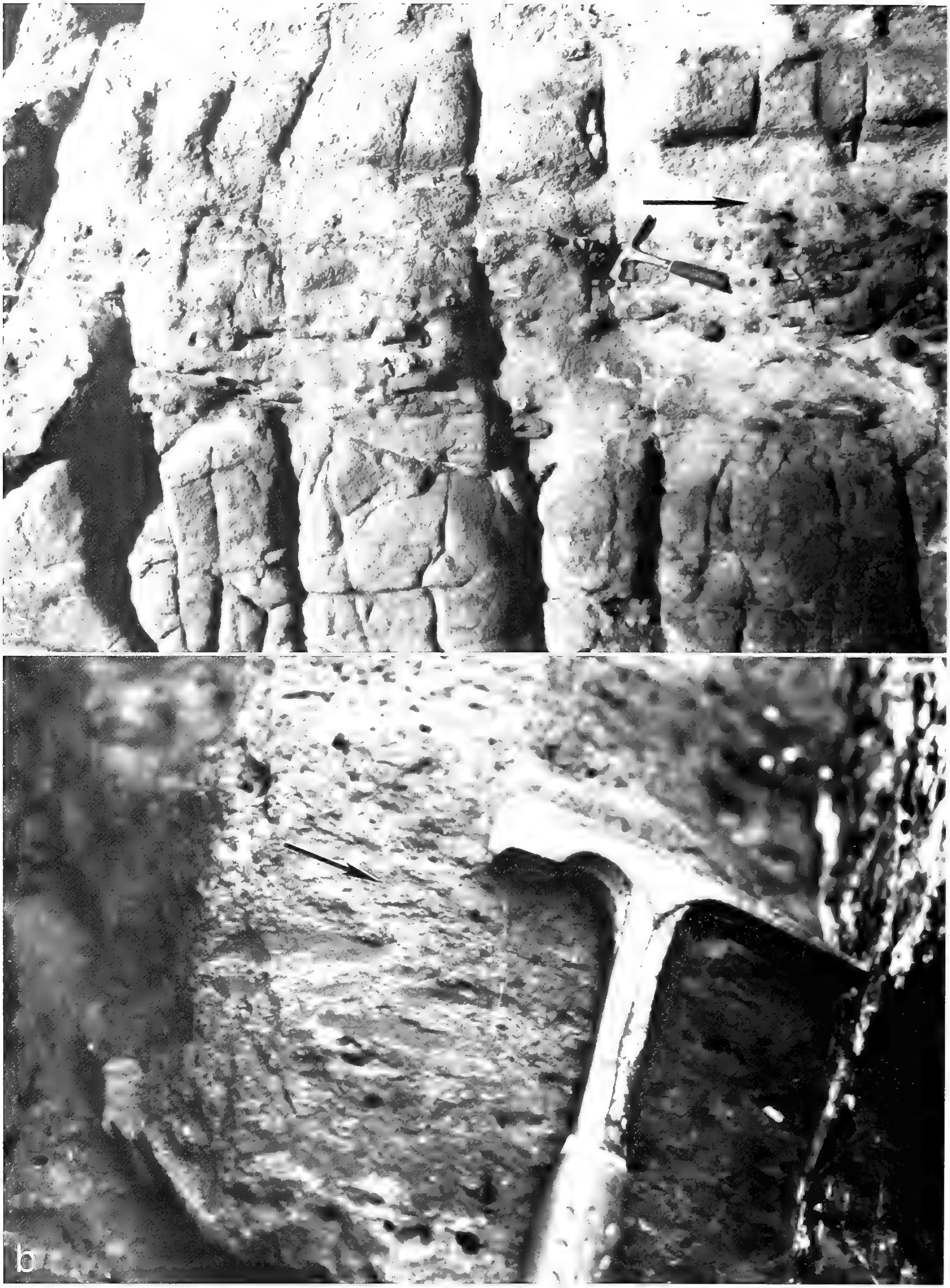

FIGURE 16.—Imbricated rip-up clasts of sandstone (*a*) and mudstone (*b*) in sandy strata: transport of large elongate clasts toward right (arrows) in both examples. Localities (in Figure 2): *a* = site 7; *b* = site 42. Hammer is 28 cm long.

FIGURE 17.—Worn rudists (*Barrettia gigas*) embedded in coarse carbonate and fossil-bearing debris-flow deposits at Vagthus Point (Judith Fancy Formation, site 6, Figure 2; photo of exposure in Figure 14*a*). Long axis of specimens is flat-lying, not vertical as in their living position; such large fossils usually occur near base of beds. Hammer is 28 cm long.

FIGURE 18.—Examples of syndepositional deformation structures. *a*, Crinkling of several sandstone layers (arrow) between undeformed strata (hammer is 28 cm long). *b*, Convolution (arrow) within one layer (15 cm thick) between several undeformed sandstone strata. Localities (in Figure 2): *a* = site 50, *b* = site 4.

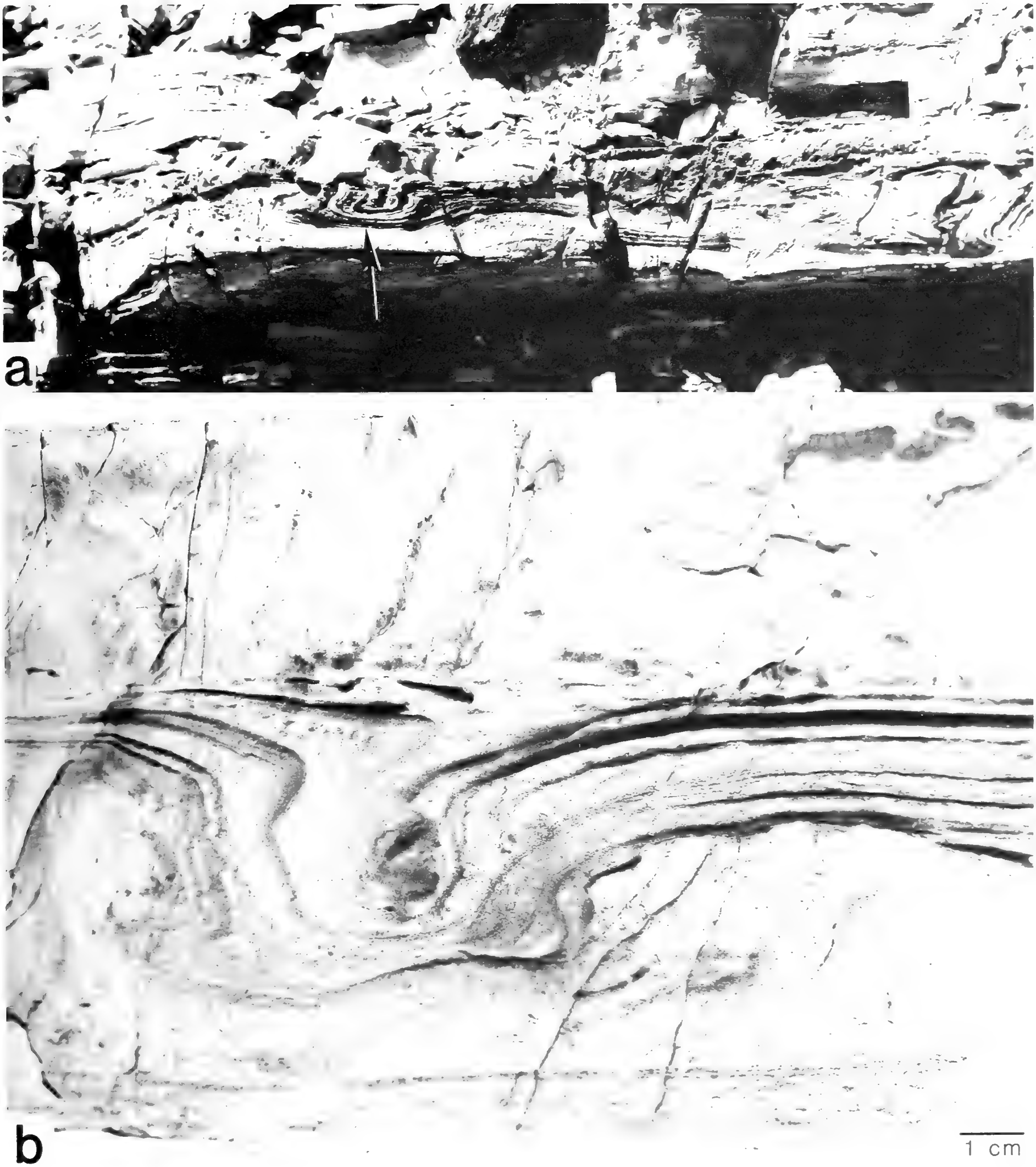

FIGURE 19.—*a*, Single highly deformed layer (arrow) of fine- to medium-grained sandstone of fairly constant thickness (7–9 cm thick); it crops out between undeformed strata at East End Point (site 19, Figure 2). *b*, Base and top of stratum are near-parallel, while laminations within most of bed have been tightly folded into convolutions along its entirety. Other examples of convolutions along this same bed shown in Figures 20 to 22.

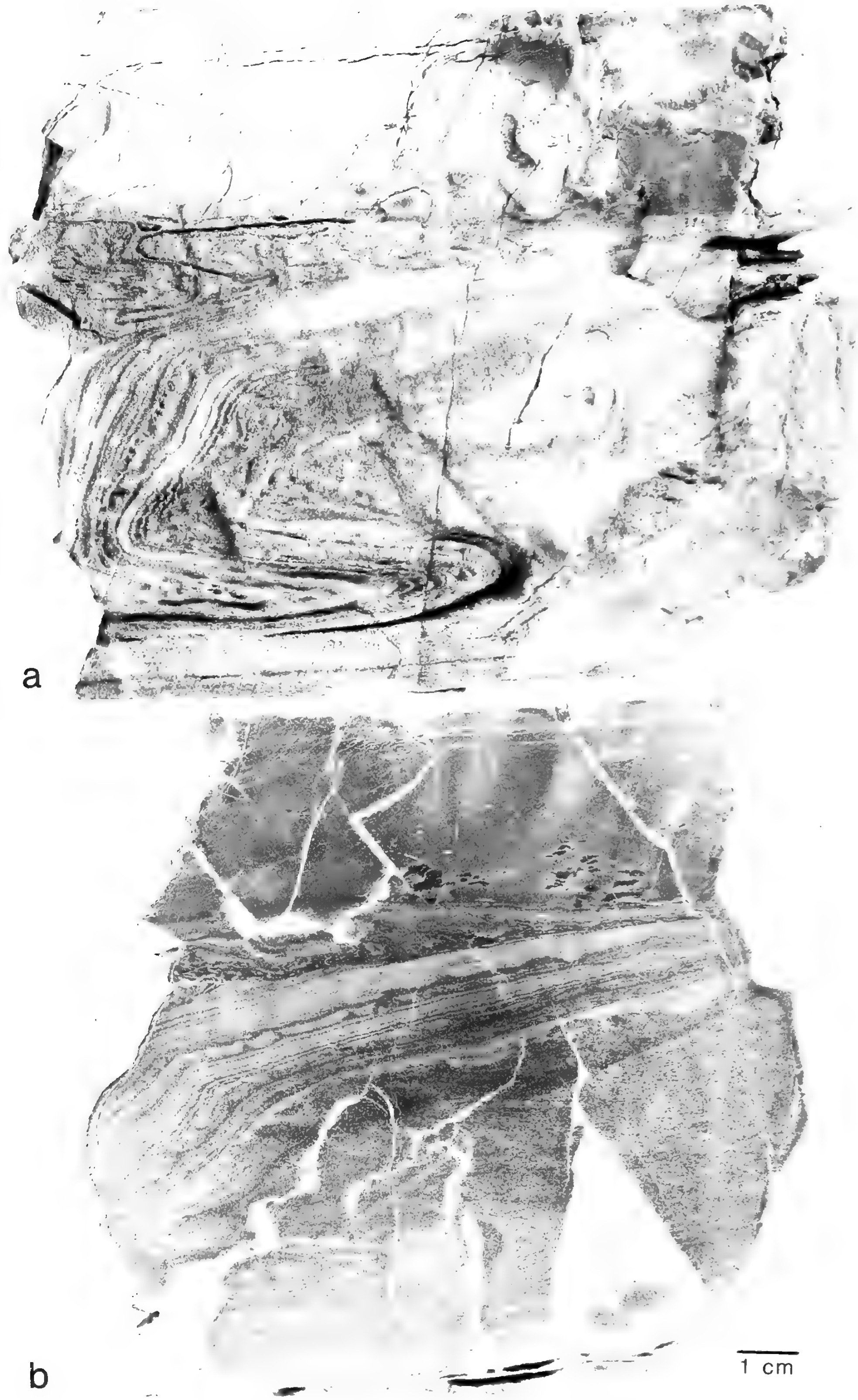

FIGURE 20.—Hand specimen showing syndepositional deformation structures (very tight convolutions) within sharp-based and -topped sandstone bed (see Figure 19*a*) at East End Point (site 19, Figure 2). *a*, Weathered surface; *b*, Polished section. Scale bar applies to all components.

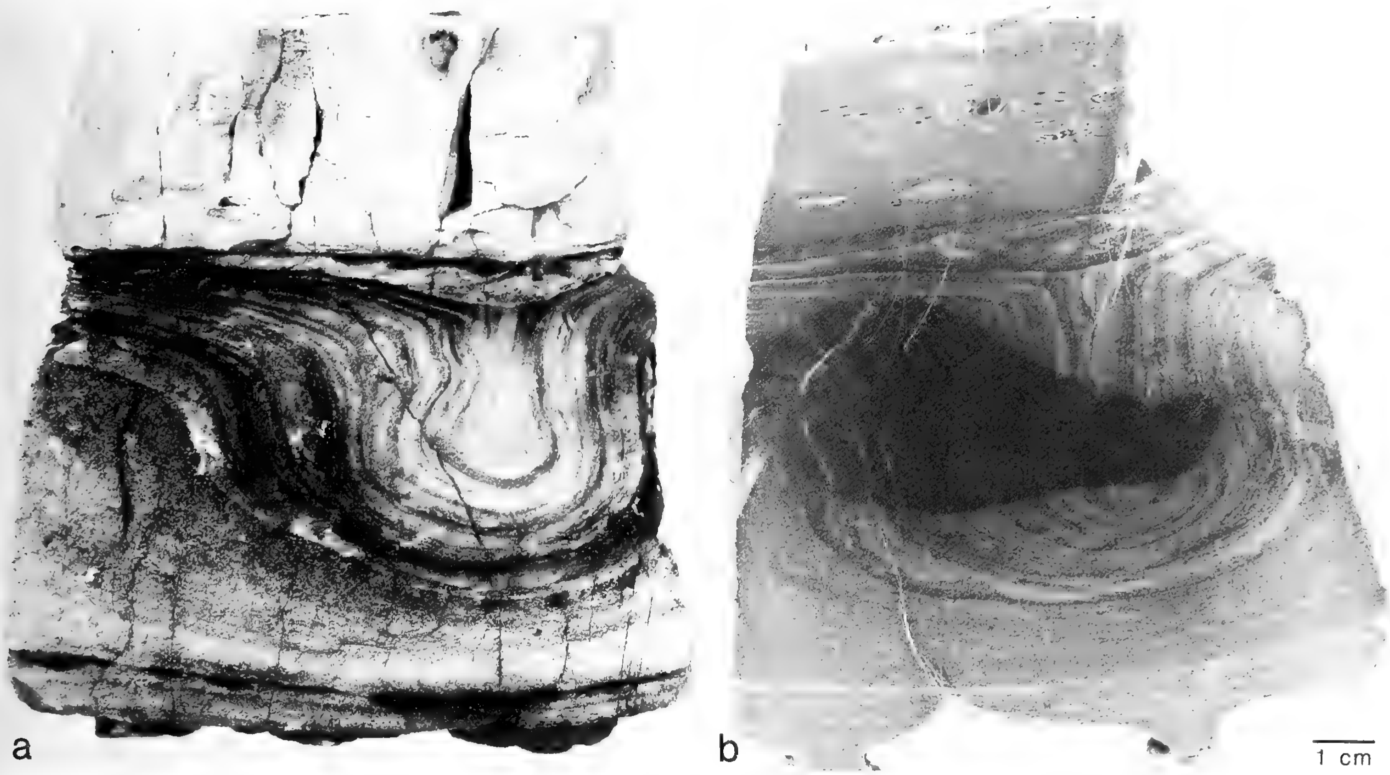

FIGURE 21.—Hand specimen showing syndepositional deformation (convolution/probable dewatering) structure within sharp-based and -topped sandstone bed (see Figure 19a) at East End Point (site 19, Figure 2). *a*, Weathered surface; *b*, polished section. Scale bar applies to all components.

from unconsolidated strata, may result from several types of events. These can include (a) sudden burial by a rapid succession of depositional events (sometimes denoted by deformed sole markings and load structures) and (b) earthquake motion as recorded by some beds that show intensely convoluted laminations in a fairly constant and continuous fashion over wide areas).

The structures of the type cited above, occurring in both the Caledonia (Figure 23) and the Judith Fancy formations, are not only frequently observed but also quite diverse in configuration. Syndepositional deformation usually affects only a part of a sandy stratum. Examples include structures primarily at the upper parts of beds (Figure 24*d,e*), those within the middle and upper part of beds (Figures 24*a–c*), and those at the base of beds (Figure 25). Some deformation features also may be post-depositional in origin, i.e., structures formed as the still-unconsolidated strata were compressed, tilted, and displaced during, and following, Late Cretaceous time. Structures that are truly syndepositional, as well as those formed subsequent to lithification (e.g., post-depositional shear/low-grade metamorphic structures; Figures 23*e,f*, 26*b,d,e*), prevail at many localities; some are difficult to distinguish.

PALEOCURRENT ANALYSIS.—The tectonic complexity and structural deformation affecting the Cretaceous sequences in St. Croix have been alluded to in an earlier section. There is, therefore, a question of reliability of paleocurrent-paleoslope and provenance/dispersal interpretations as determined from the directions of measured primary sedimentary structures. On the basis of groove markings and other sedimentary features mapped in the Caledonia, Judith Fancy, and other tuffaceous rocks, it would appear that gravity transport occurred along general north-south trends (compass orientations ranging from NE-SW to SW-NE quadrants). This is in general agreement with earlier conclusions presented by Whetten (1966b, fig. 18). At sites such as at Manchenil Point and Vagthus Point (sites 7 and 6, Figure 2), the apparent downslope-transport directions are oriented toward the south, south-southeast, and south-southwest quadrants (Figure 5). A determination of south-dipping trend of slopes with sediment dispersal from a northern source, as based on sedimentary structures and mineralogical composition, would assume minimal, post-depositional, lateral translation or rotation of Cretaceous rock units. Surface mapping coupled with subsurface exploration of the island are needed to confirm these hypotheses.

Whatever the exact direction of transport, the association of slides, slumps, sand flows, and coarse-grained turbidites in the Cretaceous Caledonia and Judith Fancy formations implies that sediment transport occurred on slopes. To accommodate

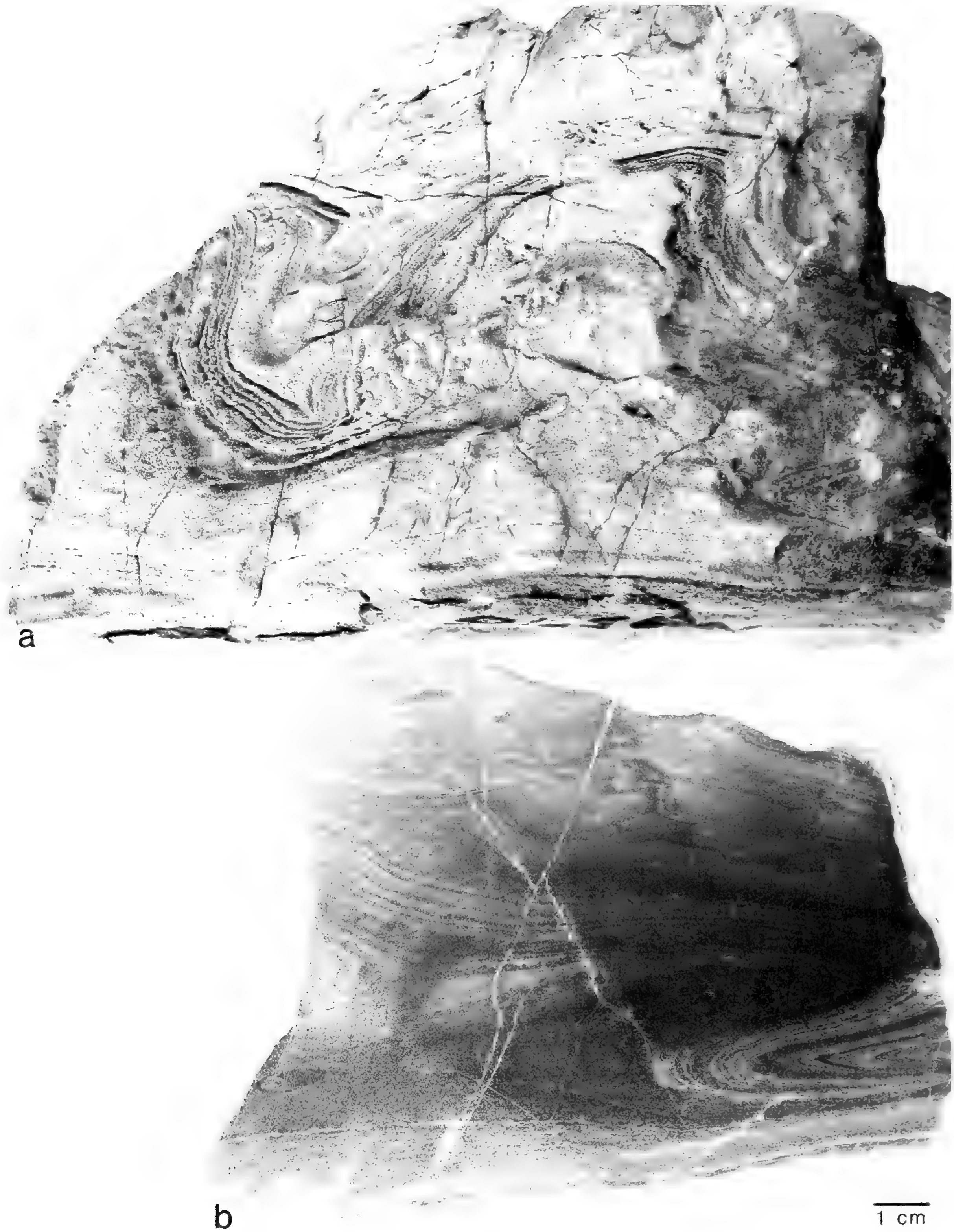

FIGURE 22.—Hand specimen showing syndepositional deformation structures (including very tight convolution and possible dewatering features) within sharp-based and -topped sandstone bed (see Figure 19a) at East End Point (site 19, Figure 2). *a*, Weathered surface; *b*, polished section. Scale bar applies to all components.

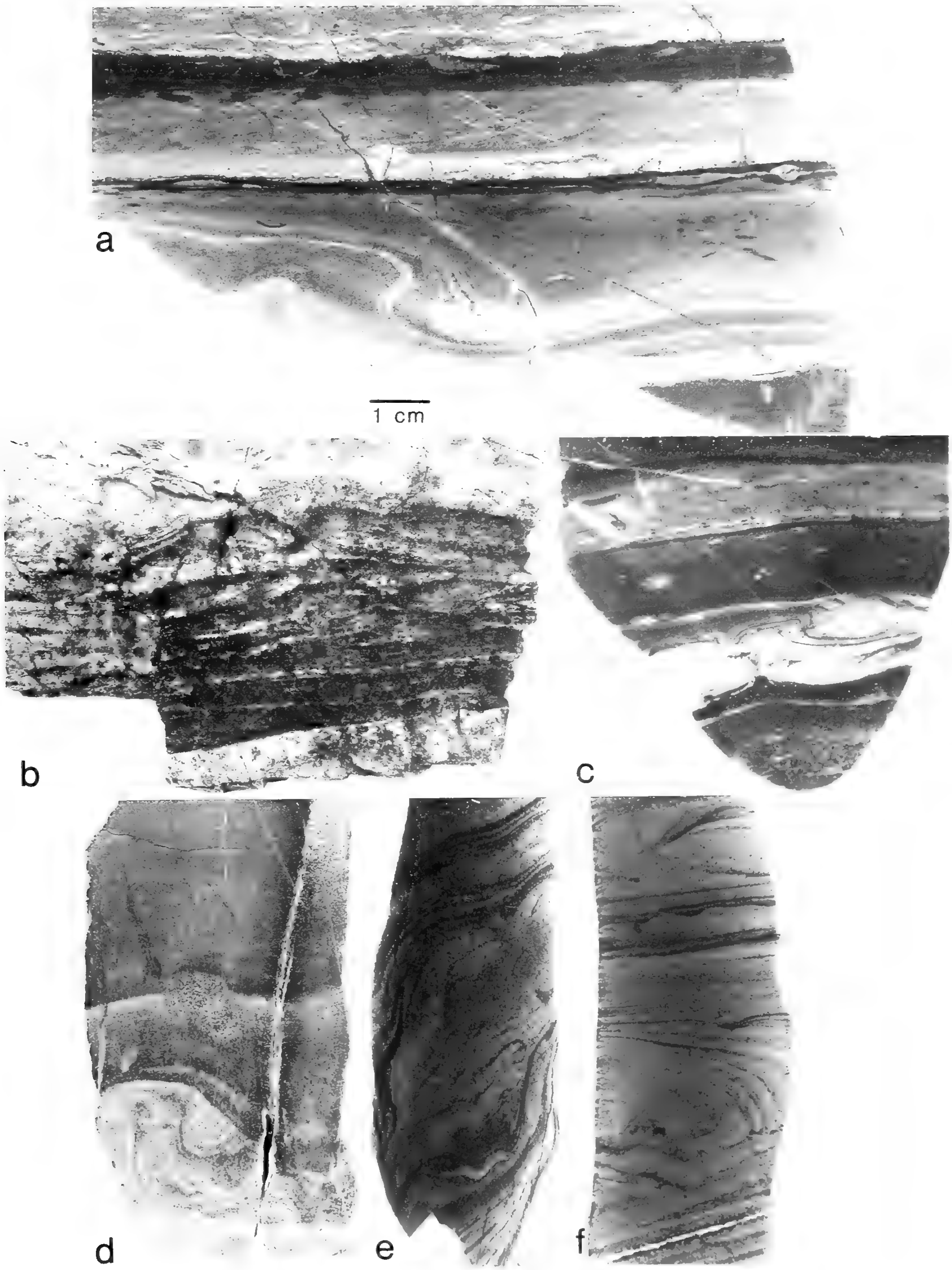

FIGURE 23.—Polished sections showing various types of syndepositional structures (including convolutions) in Caledonia Formation. Examples include those restricted to part of bed (*a*), or affecting entire layer (*c*, lower in *d*), or affecting set of laminae (*b,f*). Some structures may have a post-depositional component (possibly *e*). Localities (in Figure 2): *a,c* = site 50; *b* = site 5; *d,f* = site 23; *e* = site 52. Scale bar applies to all components.

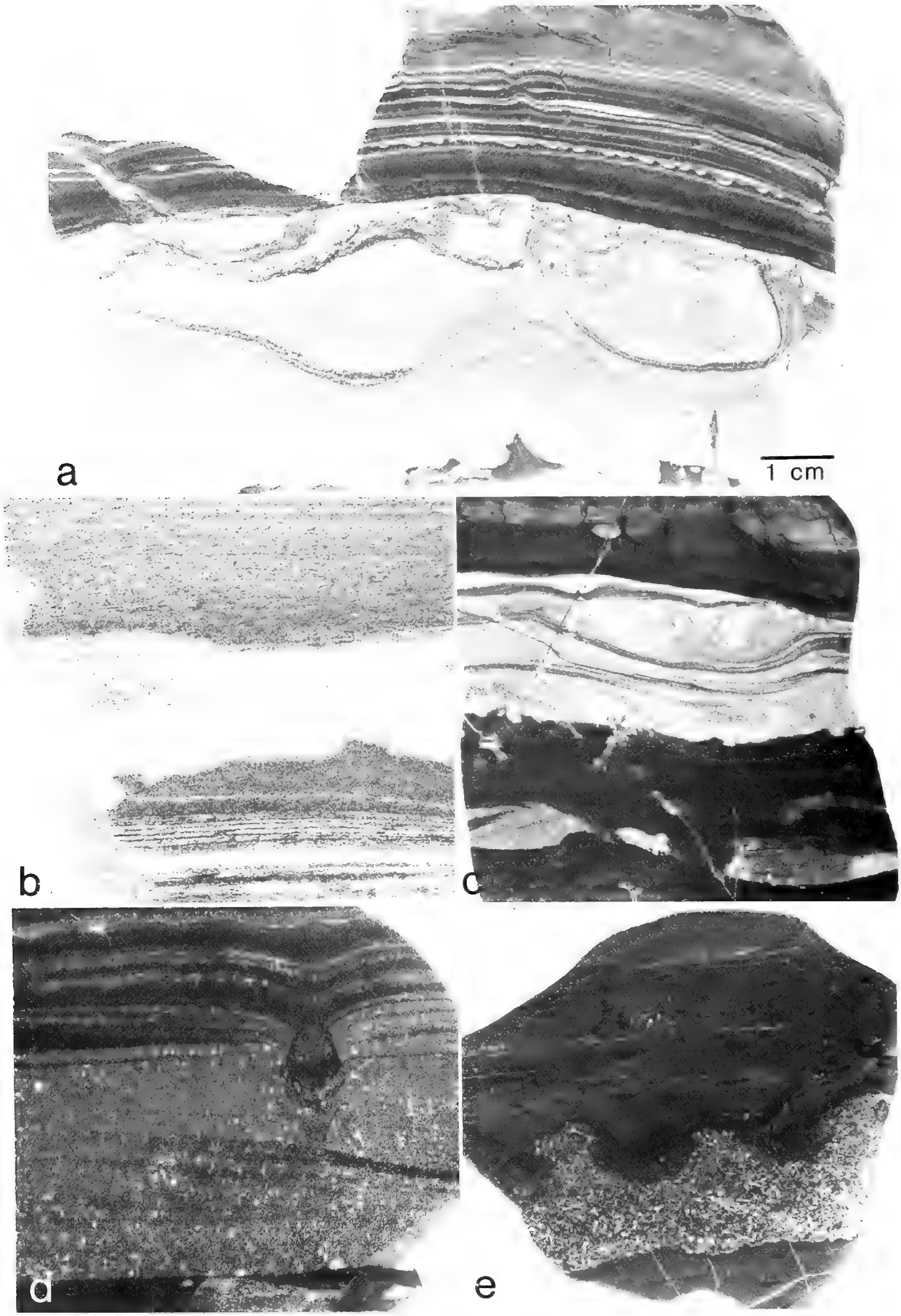

FIGURE 24.—Polished sections showing syndepositional structures (including convolutions) affecting mid- and upper parts (*a–c*), and top (*d,e*) of sandy beds, while lower parts of strata appear little or not disturbed. Sandstones in *d* and *e* are graded. Localities (in Figure 2): *a–d* = site 50; *e* = site 55. Scale bar applies to all components.

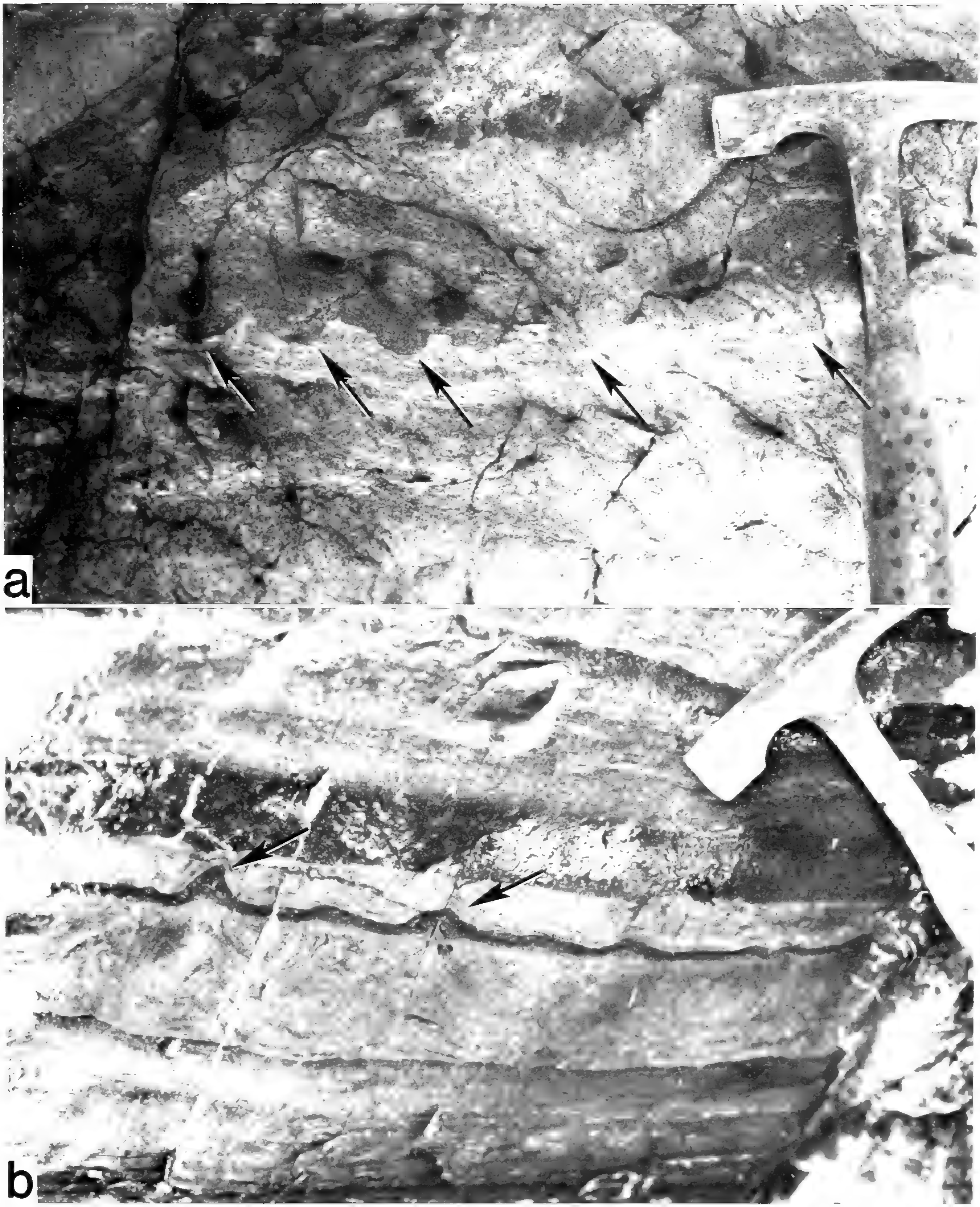

FIGURE 25.—Photographs at outcrop. (*a*) Load structures (arrows) and (*b*) load/flame structures (arrows) in lower parts of sandstone turbidites. Localities (in Figure 2): *a* = site 12; *b* = site 53. Hammer is 28 cm long.

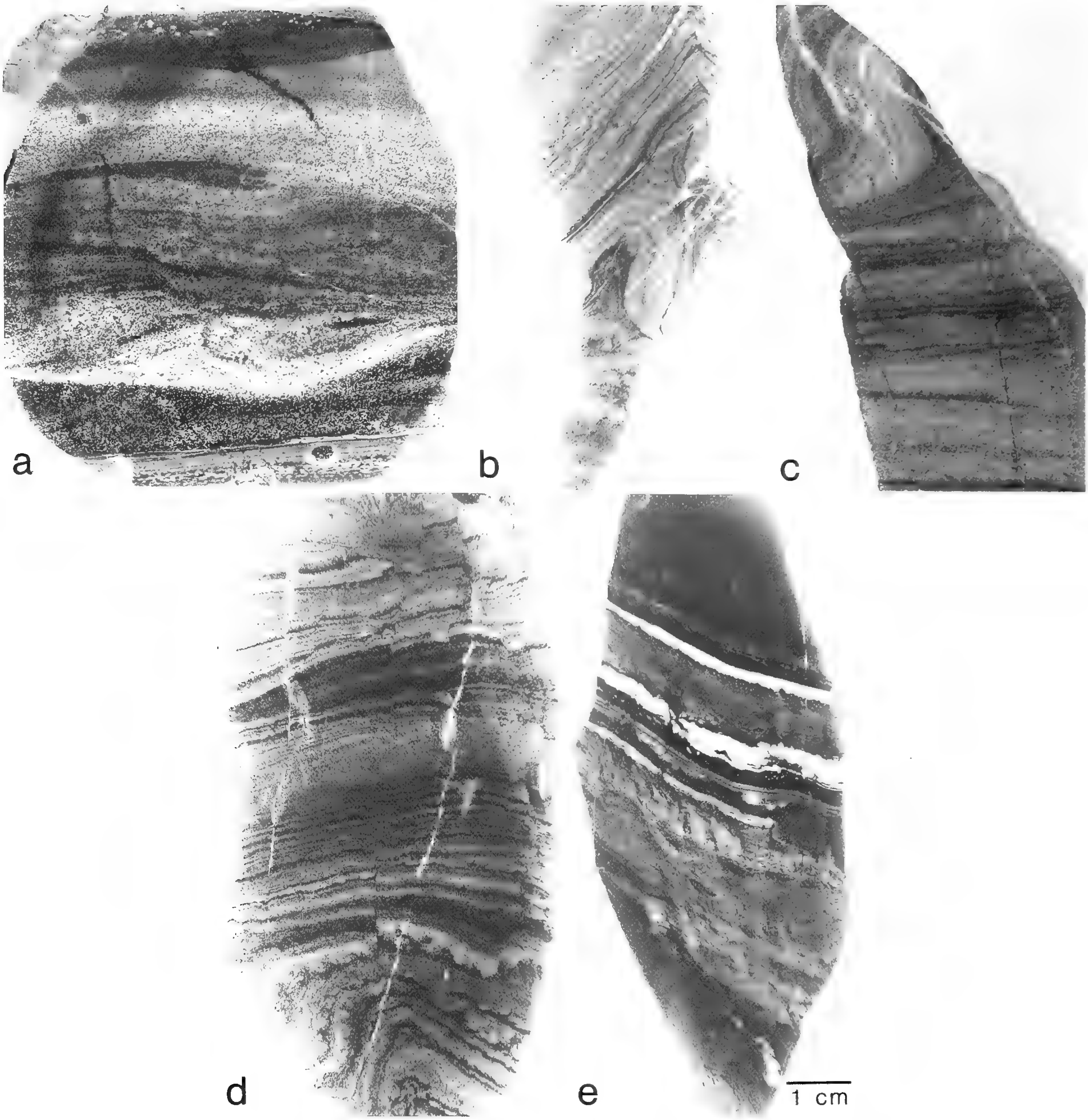

FIGURE 26.—Polished sections showing deformed structures, some (*b,d,e*) which probably have post-depositional component. Note offset of laminae in *d*. Petrographic analyses indicate recrystallization veins, and mineralogical alterations associated with low-grade metamorphism. Localities (in Figure 2): *a* = site 34; *b* = site 9; *c* = site 23; *d* = site 25; *e* = site 52. Scale bar applies to all components.

this assemblage of mass-flow deposits, most slopes were relatively steep, approximated 5°. Some slopes, locally, were probably steeper, i.e., to 10° or more. Moreover, the volcaniclastic sediments accumulated in proximal (base-of-slope), rather than distal, settings.

TURBIDITE SEDIMENTATION: THE PRELIMINARY TRANSPORT MODE

CHARACTERISTICS OF TURBIDITES ON ST. CROIX.—The gravity-driven deposits cited in the previous section (slides, slumps,

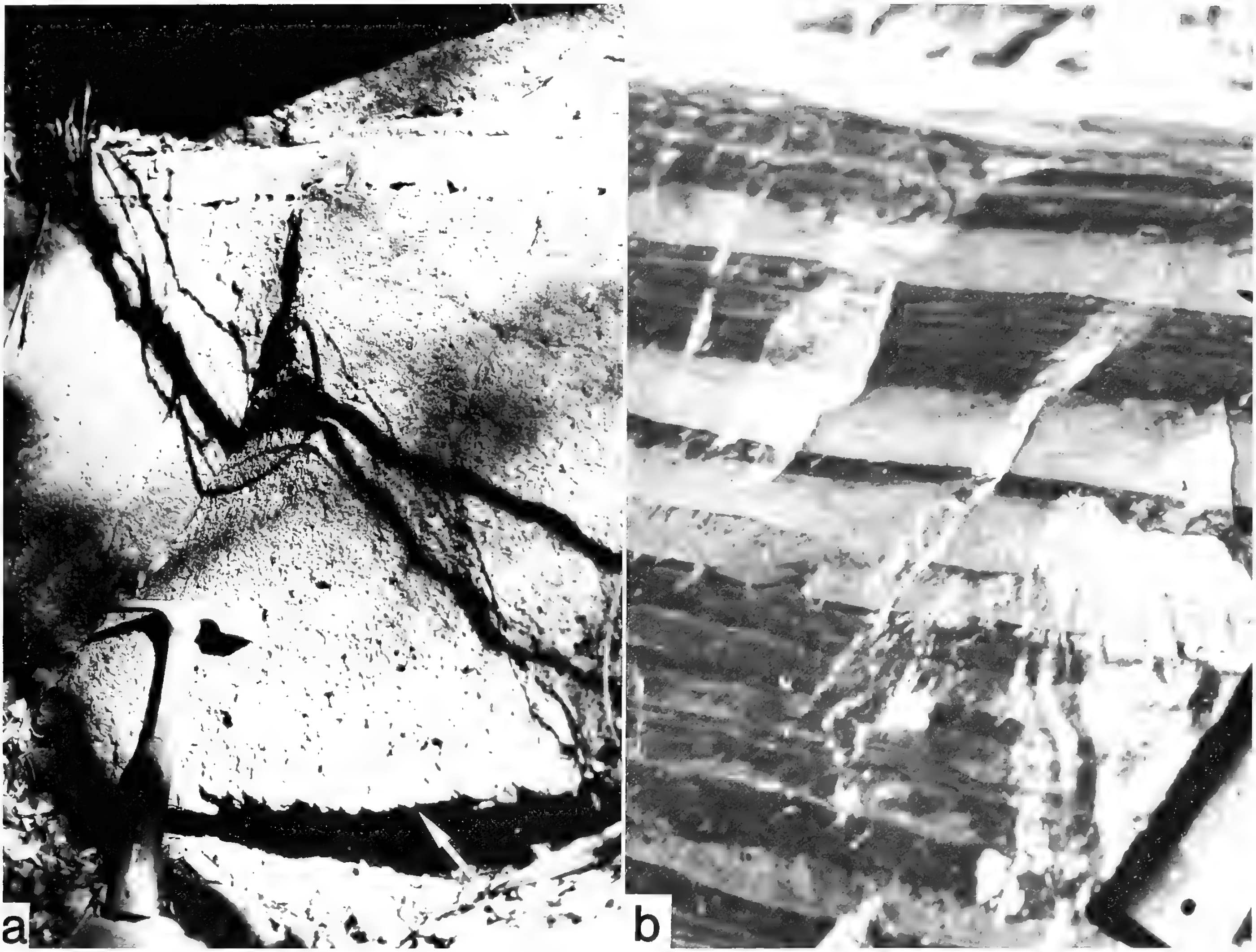

FIGURE 27.—Turbidites in ravine above Creque Dam reservoir (site 53, Figure 2). *a*, Granule and coarse sandstone massive lower division A of thick turbidite; note erosional base (arrow). *b*, Thin but complete (A–E) coarse sandstone to siltstone turbidites. Hammer is 28 cm long.

"debrites," sand-flow deposits, and very coarse turbidites), recognized as a slope assemblage, constitute only a small portion of the Cretaceous sequences on St. Croix. Most sections examined are formed largely of thin (rarely in excess of 50 cm, and usually <10 cm), medium-grained, volcaniclastic, sandstone layers (indurated to quartzite) that alternate with mudstone strata (silt and clay admixtures usually indurated to slate). Although outcrops of the Caledonia and Judith Fancy formations are flysch-like in general appearance (Figures 6*a*, 14*a*), it is of note that the majority of localities include only a low proportion (usually <20%) of continuous, even-bedded, sandstone strata that, on close scrutiny, would be identified with certainty as turbidites.

The term "turbidite," as used herein with reference to sandy layers, is restricted to a stratum that displays an established vertical sequence (partial or complete) of bedform intervals as reviewed in the following paragraph, plus at least a minimal amount of textural upward-fining (graded bedding). There is usually a sharp basal contact with the underlying mudstone (Figures 6*b*, 27*a*) and a less well-defined (sometimes quite subtle) upper bed contact with the overlying mudstone layer (Figures 27*b*–31). Graded bedding is of the type where fine grains are present as matrix throughout; the proportion of coarser grains, however, gradually decreases upward (Figures 30*a*–*d*, 31*b*). Climbing ripples (Figure 23*b*), sole markings (Figures 31*d*, 33–35), convolute laminations (Figure 23), and rip-up clasts (Figures 6*b*, 29*a*) are additional attributes, but not always present.

In thin section (Figures 35*b*, 36*c*) laminae usually appear highlighted by darker finer-grained (clay/silt) layers rather than

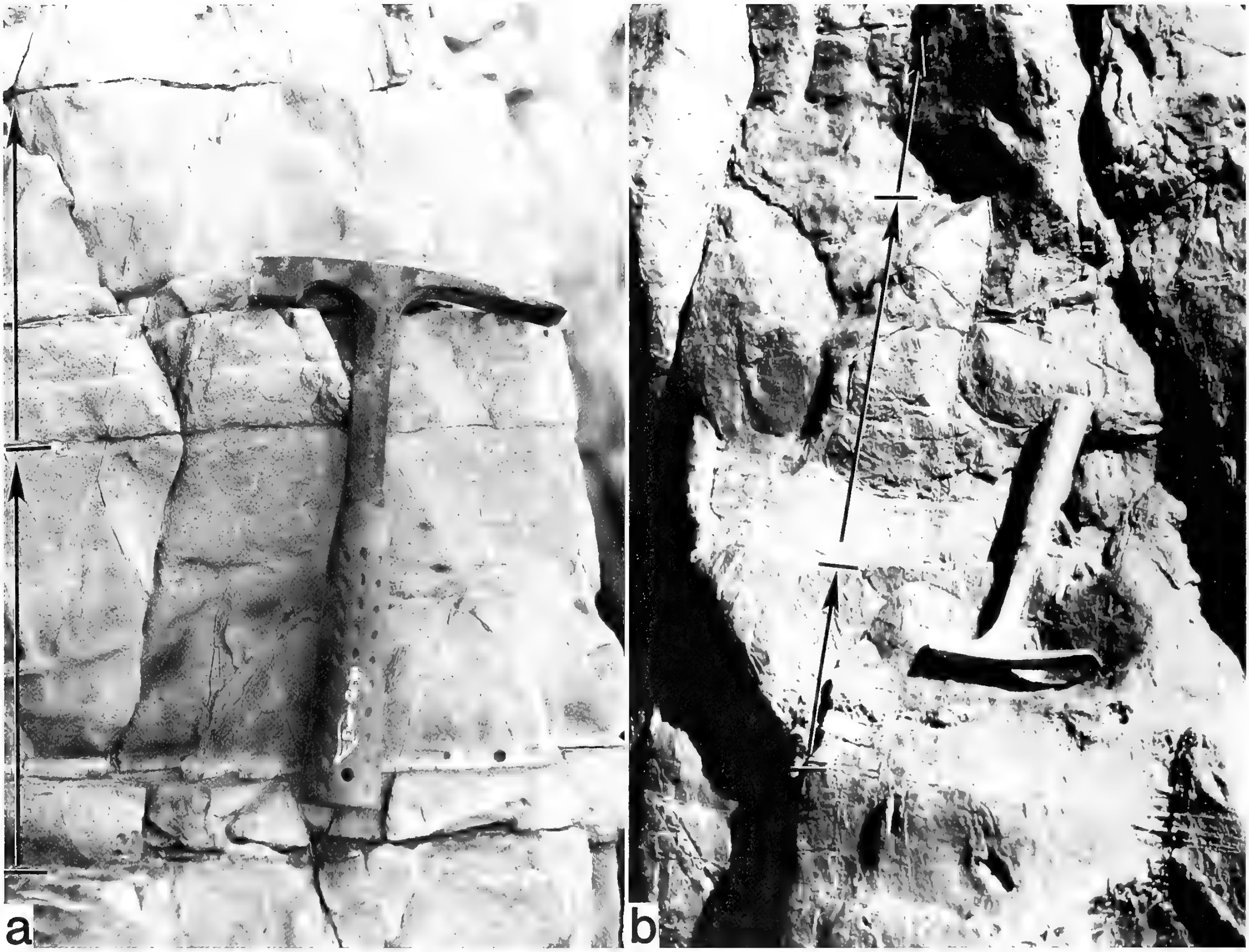

FIGURE 28.—Sections of superposed A–B and B–C turbidites. *a,* Lower turbidite division is massive graded (A). *b,* Lower division is plane laminated (B). Localities (in Figure 2): *a* = site 23; *b* = site 43. Hammer is 28 cm long.

by concentrations of heavy minerals. Sorting is moderate to poor. Granule- and sand-sized grains are usually in contact (Figure 30) but, in some instances, may also be separated by matrix (fine-grained material of silt and clay size, Figure 37*b,c*). No conclusive observations are made with reference to sand-size grain orientation. Larger, elongate particles, however, are sometimes imbricated (Figure 37*c,d*). The above observations that pertain to the texture, fabric, and matrix of these Cretaceous turbidites should take into account that rocks at most localities have been subjected to low grade metamorphism. This latter factor has resulted in disruption of the original grain-to-grain and grain-to-matrix contact, and also in partial recrystallization and mineralogical changes, especially of the fine-grained material.

Most importantly, turbidites display fining upward and the well-defined vertical sequence of bedform intervals, or divisions (cf. Bouma, 1962, fig. 8): a basal-graded (sometimes termed massive) term (A), ranging from granule- to coarse-silt size (Figure 30*a,b*); a horizontal- or plane-laminated term (B) such as those in Figures 28*b,* 31*d,* 32c, 35, and 38a; a ripple cross-laminated division (C), sometimes with wavy, climbing, and/or convolute laminae (Figures 32*b,* 35, 36*d–f*); an upper parallel laminated term (D), finer-grained than the (B) division (Figure 28); and a poorly defined mudstone (usually slate) division (E) above the A–D sandstone layer (Figures 31*a,* 38*a*). Hydrodynamic interpretations of these divisions have been made by Walker (1965), Middleton and Hampton (1973), Stow and Piper (1984), and others.

COMPLETE VERSUS INCOMPLETE TURBIDITES.—At most outcrop localities in eastern and western St. Croix and on Buck Island, complete turbidites displaying all the A to E terms (Figure 28*a*) account for only a small percent of all sandstone

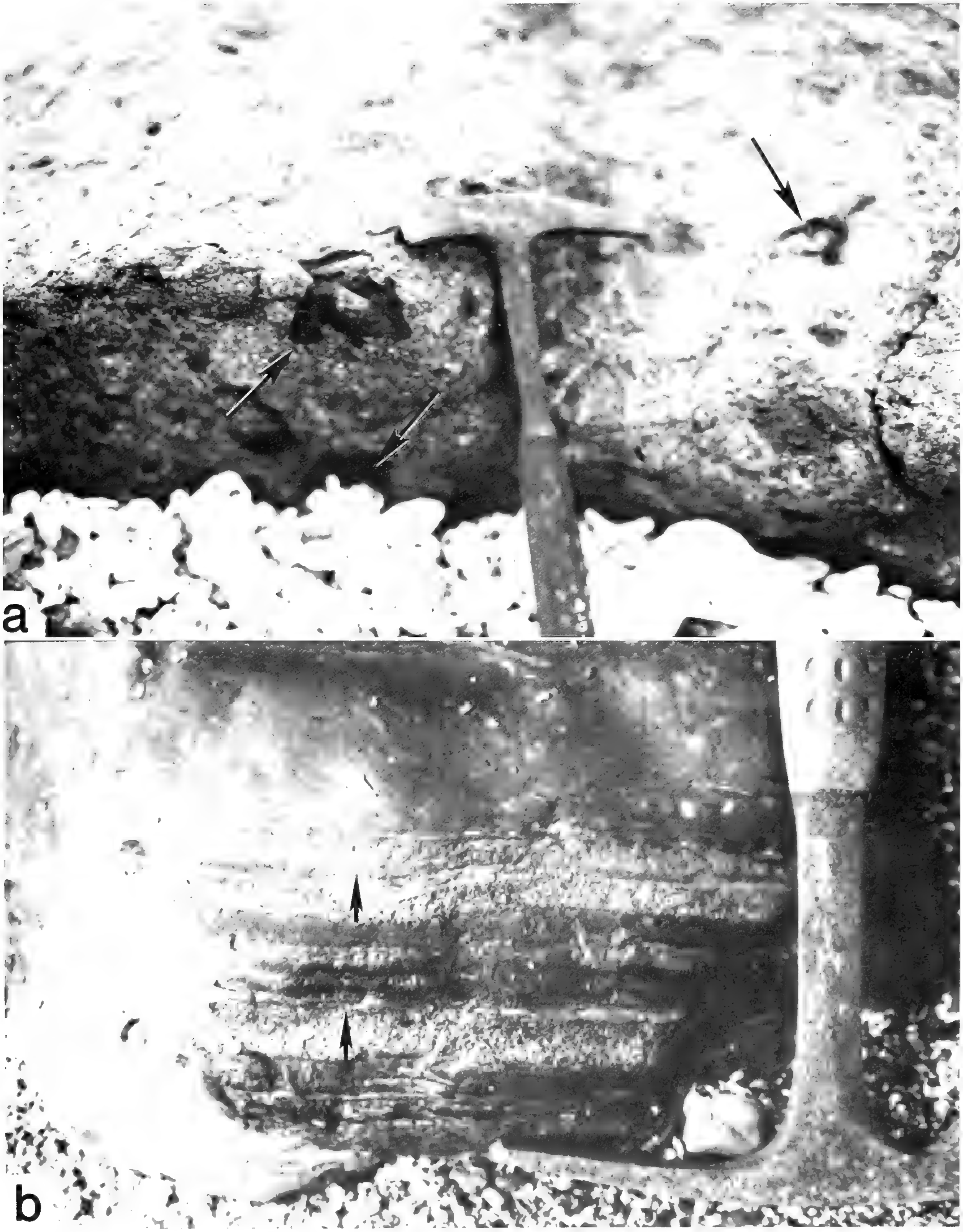

FIGURE 29.—*a*, Rip-up siltstone clasts (arrows) in basal massive (A) part of thick turbidite. *b*, Thin but very coarse sandstone turbidites. Note sharp base and well-developed fining-upward trends (arrows). Localities (in Figure 2): *a* = site 16; *b* = site 50. Hammer is 28 cm long.

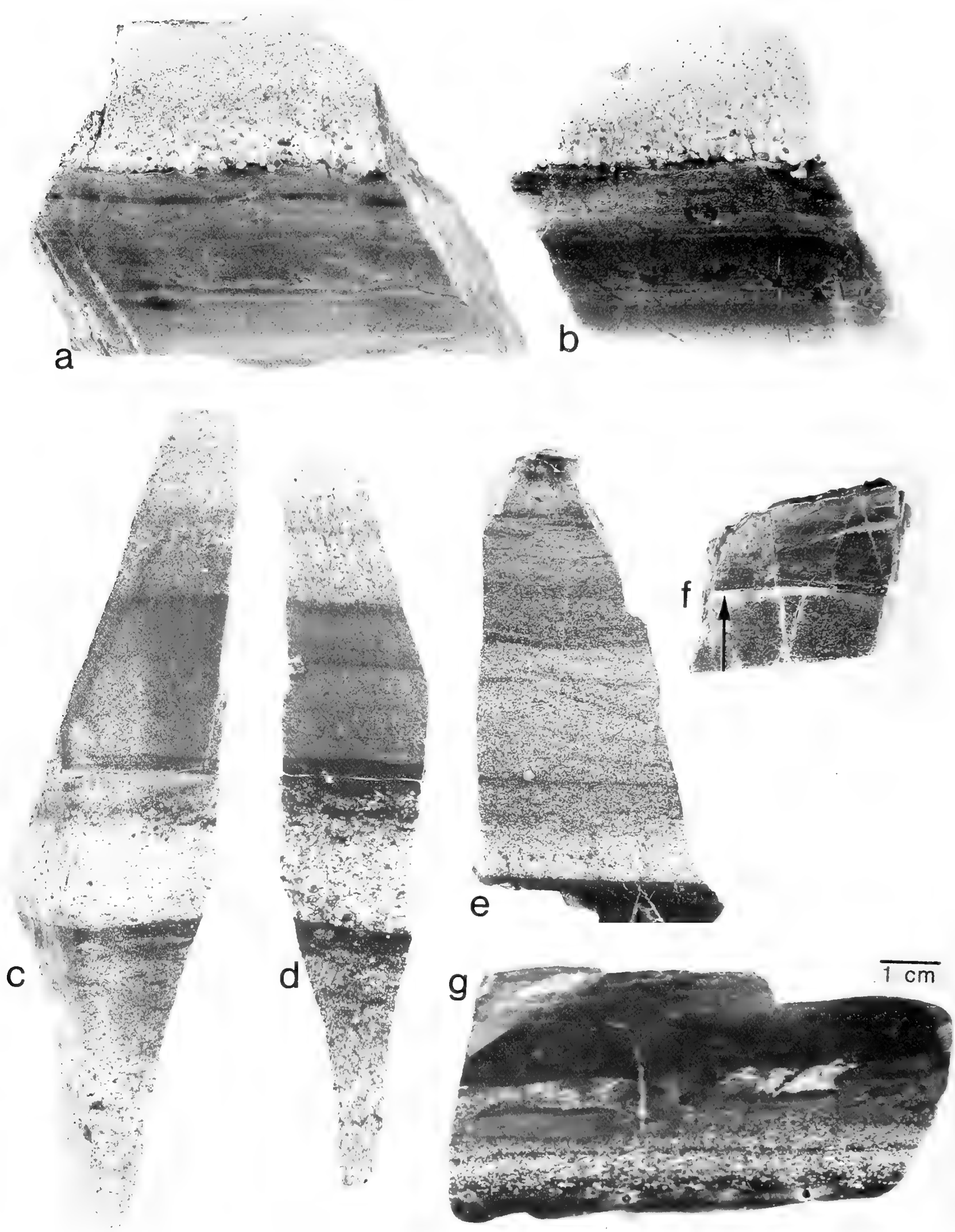

FIGURE 30.—Polished sections (*a,c,g*) and large thin sections (*b,d,e,f*) of graded volcaniclastic sandstone turbidites. *a–d, g,* Sharp-based, coarse-grained sandstone, massive A units. *e,f,* Medium-grained sandstone A division grading up (arrow) to B and C divisions. Localities (in Figure 2): *a,b* = site 22; *c,d* = site 53; *e* = site 17; *f* = site 19; *g* = site 17. Scale bar applies to all components.

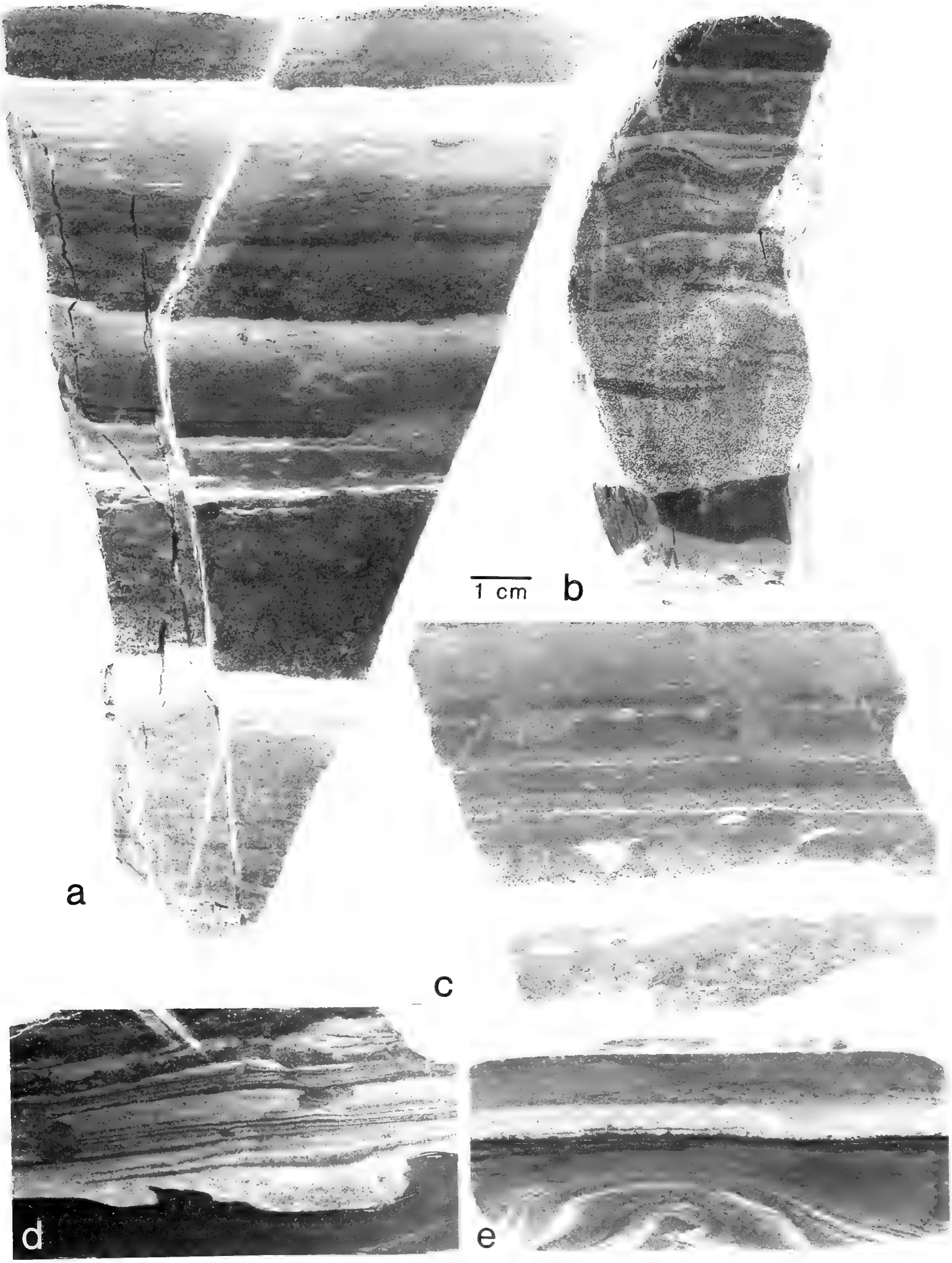

FIGURE 31.—Polished sections of thin-graded, volcaniclastic sandstone to siltstone turbidites showing sharp base; note erosional base, loads and flame structure in *d*. Localities (Figure 2): *a,c,d* = site 57; *b* = site 18; *e* = site 50. Scale bar applies to all components.

FIGURE 32.—*a*, Complete A–E sandstone turbidite. *b*, Sandstone turbidite with climbing ripples in lower part topped by upper horizontal laminated D division. *c*, Upper thin sandstone (below pen) comprising largely B planar laminated division. Localities (Figure 2): *a,c* = site 22; *b* = site 50. Pen is 14 cm and hammer is 28 cm long.

FIGURE 33.—Base-of-bed sole markings and erosional structures in sequence at Point Cudejarre (site 18, Figure 2). *a*, Large, cut-and-fill, erosional, scour depression (arrow) in coarse sandstone layer. *b*, loads and flame structures (arrows) at base of turbidite. Hammer is 28 cm long.

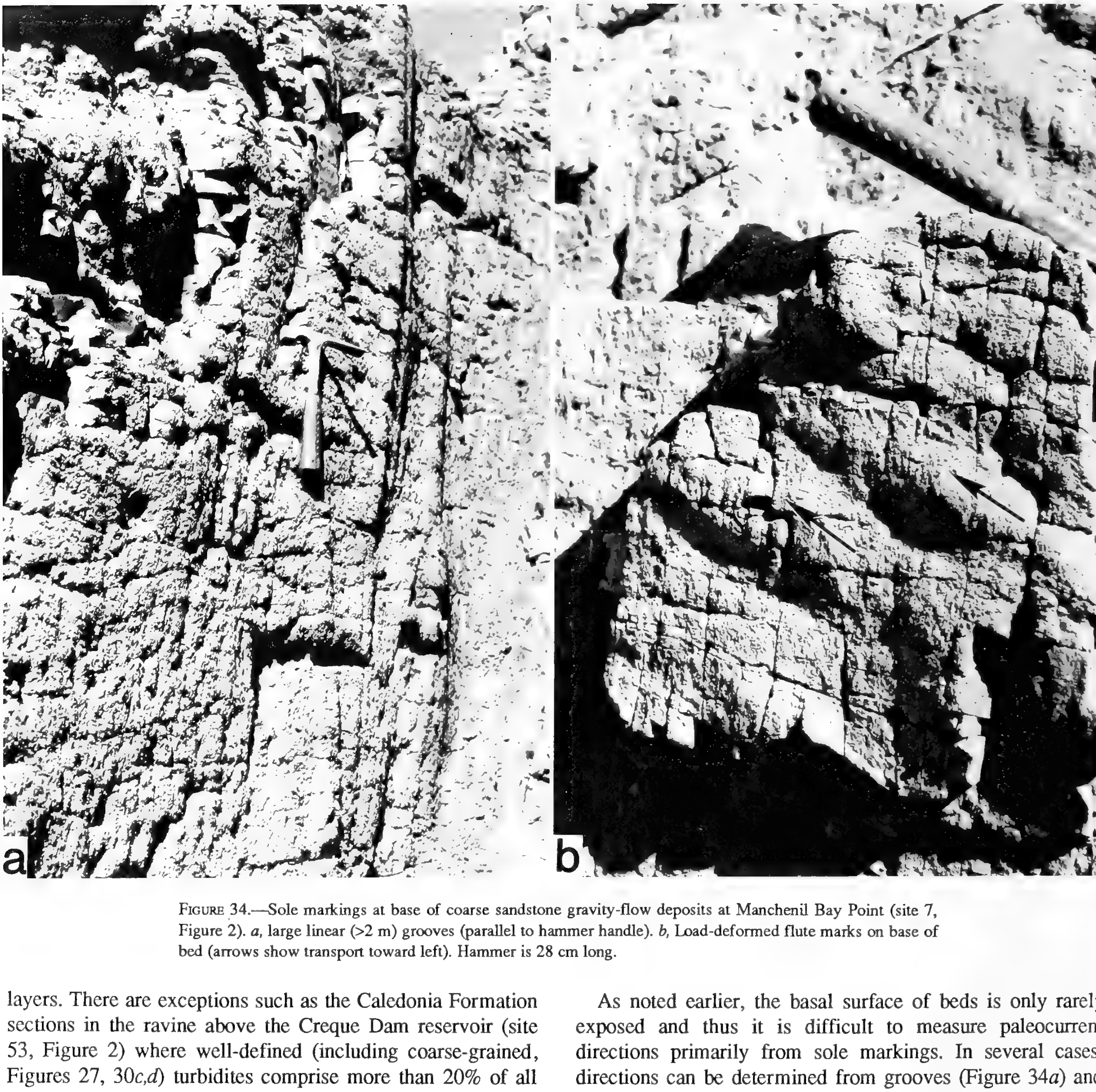

FIGURE 34.—Sole markings at base of coarse sandstone gravity-flow deposits at Manchenil Bay Point (site 7, Figure 2). *a*, large linear (>2 m) grooves (parallel to hammer handle). *b*, Load-deformed flute marks on base of bed (arrows show transport toward left). Hammer is 28 cm long.

layers. There are exceptions such as the Caledonia Formation sections in the ravine above the Creque Dam reservoir (site 53, Figure 2) where well-defined (including coarse-grained, Figures 27, 30*c,d*) turbidites comprise more than 20% of all the sandstone beds (cf. Whetten, 1966, pls. 4 and 5), Hams Bluff (site 50, Figure 2), the northwest coast of St. Croix (Figure 38*b*), and locally along the coast of Buck Island. Also observed are the coarse-grained sand to granule and even pebble-rich (Figure 14) A to E turbidites preserved in some Judith Fancy Formation localities such as Vagthus Point (site 6, Figure 2). Graded units of the type described above, particularly the coarse ones displaying an orderly A to E or B to E sequence of bedform divisions, are interpreted as proximal turbidites.

As noted earlier, the basal surface of beds is only rarely exposed and thus it is difficult to measure paleocurrent directions primarily from sole markings. In several cases, directions can be determined from grooves (Figure 34*a*) and cut-and-fill structures (Figure 33*a*), indicating a general N-S orientation; more rarely, flute marks (Figure 34*b*) show a specific (southerly) direction. Such paleocurrent measurements are sometimes confirmed by the orientation of foreset laminations in the same bed (Figure 35). The observations made in this study tend to support Whetten's conclusion (1966b:231–232) that downslope transport was primarily oriented toward the south (Figure 5), that is, in a direction away from major postulated volcanic and clastic sources located to the north.

Summarizing from the above observations, then, it is recognized that some sandstone beds at most outcrop localities fully qualify as turbidites. One of the more significant attributes of such layers is a basal-graded term, sometimes massive but matrix-rich, usually in sharp or erosional contact with the underlying mudstone. Most features illustrated in Figures 6*b* and 27 to 30 are indicative of a sudden but progressive release of grains from a sandy mud flow of decreasing concentration. Climbing ripple (or ripple-drift) bedding, also associated with some graded beds (Figure 32*b*), usually records weakening hydrodynamic conditions in which a very large amount of sand is suddenly available for deposition (cf. McKee, 1966). Much more frequently recognized at almost all localities, however, are the ripple foreset- and cross-laminations that form a large part or all of many sandy strata. It is these laminated deposits that, at least on first evaluation, have suggested truncated base cut-out turbidites (cf. Bouma, 1962, fig. 11). More specifically, it is largely on the basis of these dominant and nearly ubiquitous structures, i.e., foreset and cross lamination, and rippled bedforms (illustrated in the next two sections of this study) that earlier workers (Whetten, 1966b, 1974; Speed et al., 1979:629) interpreted many of the Caledonia laminated-sandstone layers as distal turbidites. In this respect, the interested reader is directed to the interpretion of C–E turbidites as distal turbidites presented by Bouma and Hollister (1973:89).

The mudstones (slate and fine-grained tuffaceous layers) between sandstones on St. Croix have earlier been attributed to pelagic "rain" or, possibly, deposition from the rearward part of turbidity currents. Some of these layers examined in large thin-section, displaying subtle grading and lamination, in fact appear to have a turbidite origin on the basis of criteria defined by Piper (1978), Stow and Shanmugan (1980), and Stanley (1981).

Questionable Turbidites.—A problem of accurate interpretation remains. It is quite natural that while mapping sections in the field most of the attention at any one of the exposures would be placed on the more obvious or better-defined strata. Thus let us assume, for example, that some distinct turbidites, whether they show several or all of the A to E divisions, have been identified at an outcrop. There may then be a tendency to less rigorously examine the many other sandstone layers in the section and interpret these as turbidites as well, even if their origin is not clearly evident. This is commonly the case with the thin (sometimes to 30 cm, but usually <3 cm), well stratified, sandy layers with poorly exposed or preserved structures in Cretaceous formations on St. Croix. Such layers have been identified as turbidites even in cases where they do not display the essential turbidite attributes listed earlier in this section. Repeated visits on subsequent trips to a number of Caledonia and Judith Fancy localities have revealed that, tempting as it may be to call them turbidites, at least half of these thin sandstone layers do not reveal graded bedding (compare, for example, Figure 39*a*,*b*).

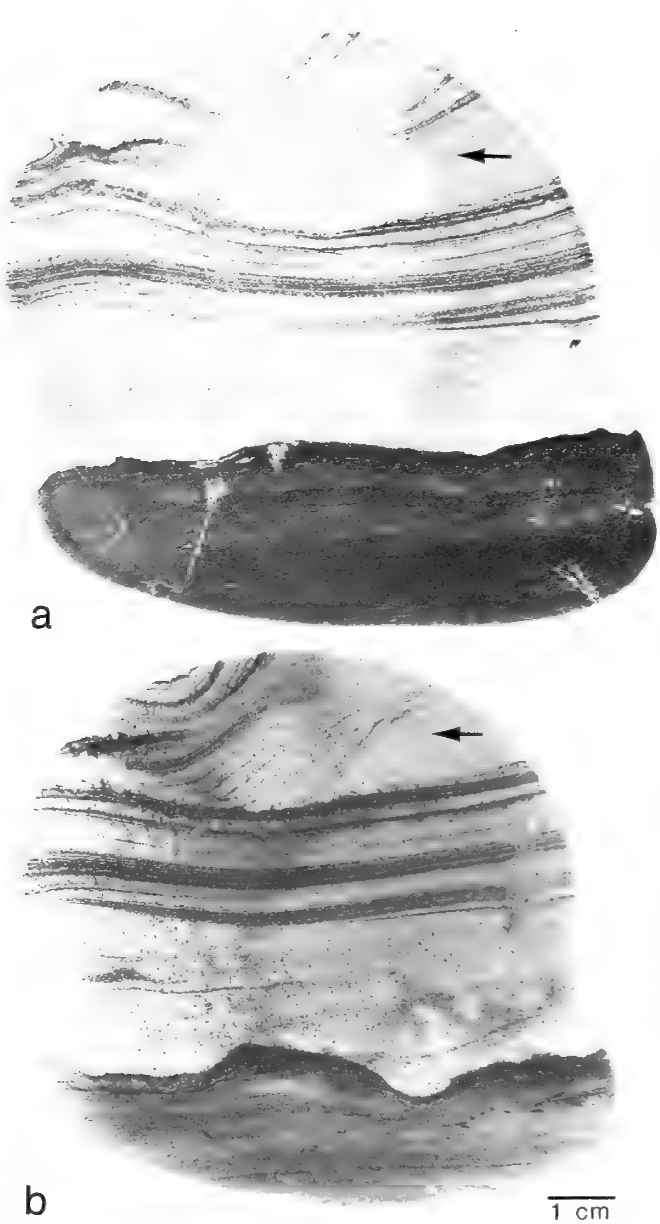

Figure 35.—Polished section (*a*) and thin section (*b*) of Caledonia Formation sandstone turbidite showing thin A and well-developed B and C divisions. Somewhat deformed foreset laminae in C division show transport to left (arrows). Note irregular load-deformed base. Sample collected at Hams Bluff (site 50, Figure 2). Scale bar applies to all components.

Moreover, more than half of the layers do not actually conform to the turbidite criteria of an ordered vertical sequence of sedimentary structures, i.e., the A to E, B to E or C to E divisions defined by Bouma (1962) and other authors.

Closer inspection indicates that many (and at some localities, the majority) of sandstones display, in addition to an inversion or irregularity in the vertical sequence of divisions, a sharp (sometimes reverse-graded) upper stratal surface, and/or laminae (some extending from the base to the top of a bed). The laminae are formed by concentrations of heavy minerals,

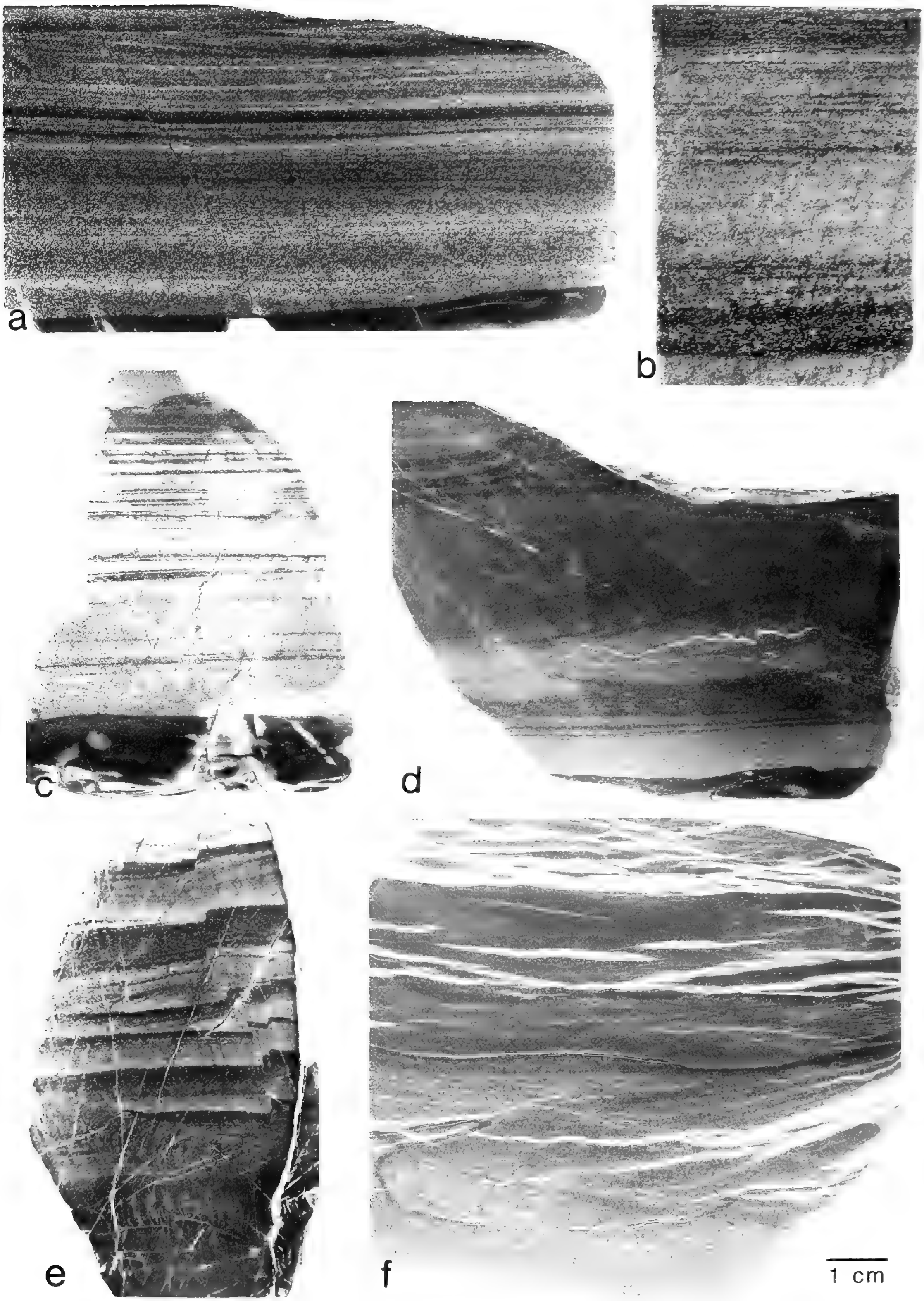

FIGURE 36.—Polished sections of thin sandy B–E (*a–c*) and C–E (*d,e*) turbidites. Note post-depositional effects such as vein filling (*d*), small-scale "micro-fault" and offsets (*e*) and extensive recrystallization associated with low grade metamorphism (*f*). Localities (Figure 2): *a* = site 1; *b* = site 18; *c,f* = site 50; *d* = site 52; *e* = site 9. Scale bar applies o all components.

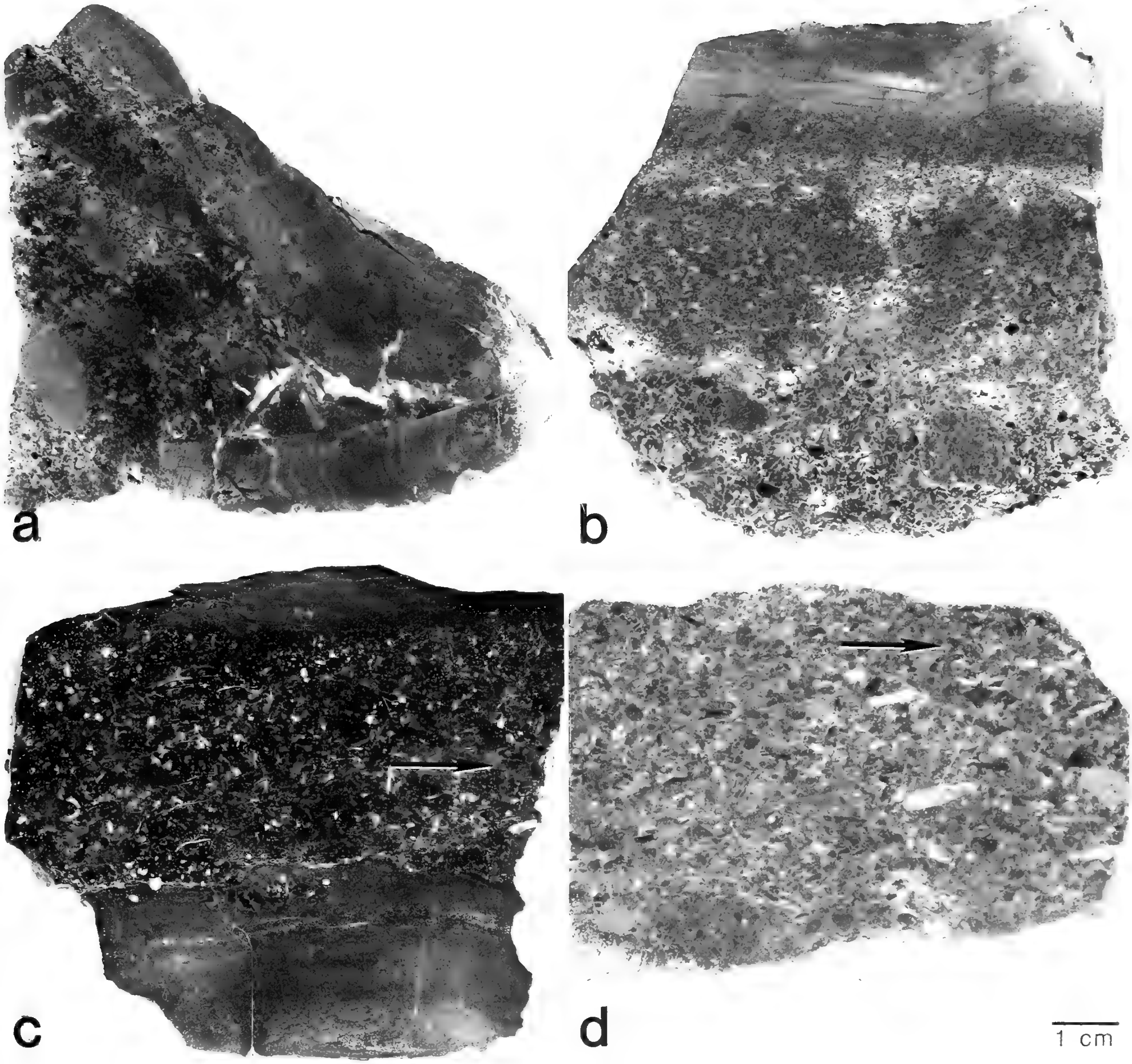

FIGURE 37.—Polished sections of coarse, carbonate-volcaniclastic deposits emplaced by sediment-gravity flows, collected at Vagthus Point (site 6, Figure 2). *a*, Rudist fragment (along margin) embedded in a debris-flow unit. *b*, Graded turbidite. *c,d*, Coarse sand-flow deposits showing imbrication of some elongate particles (arrows show transport toward right). Scale bar applies to all components.

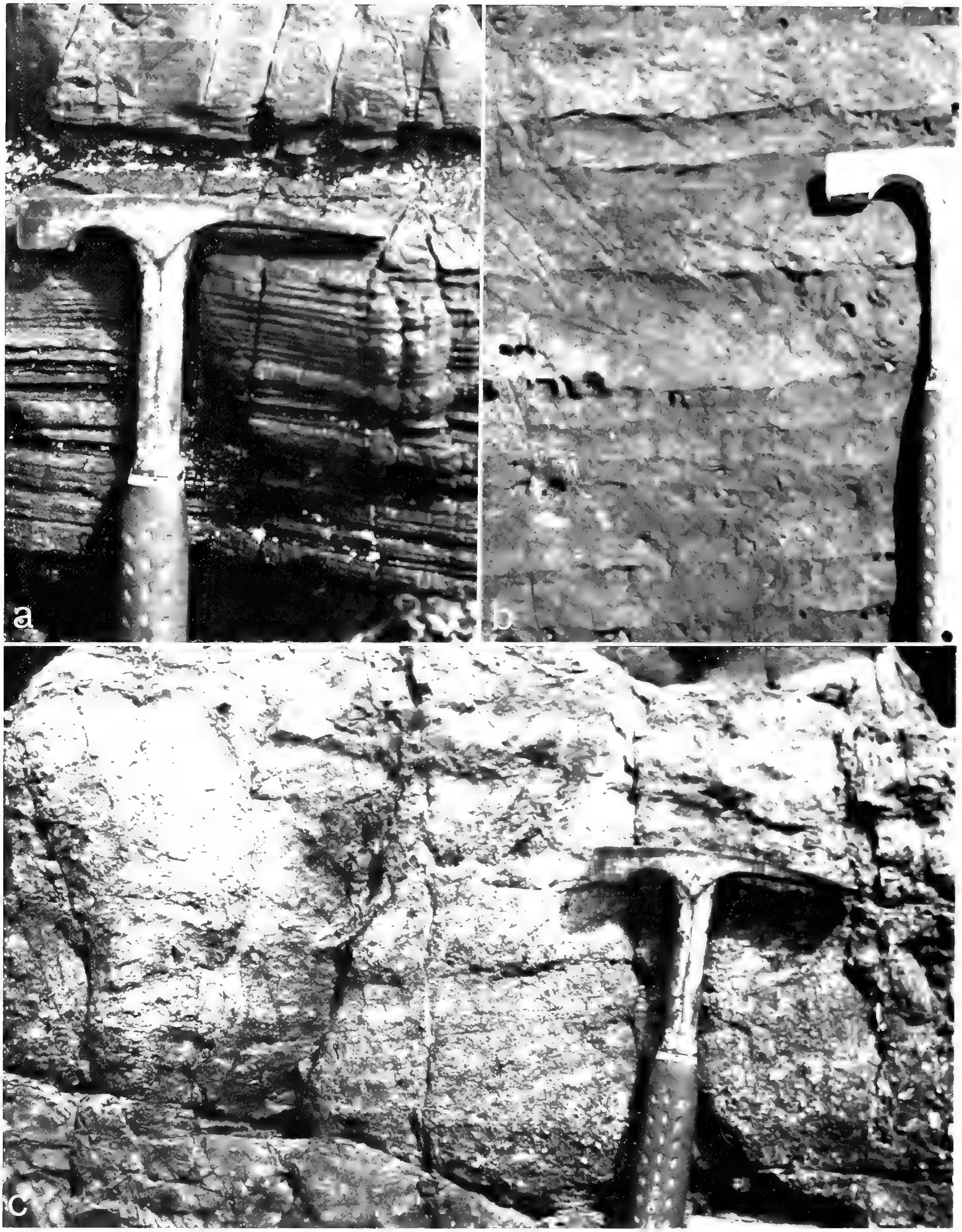

FIGURE 38.—Examples in field of sandstone strata in northwestern part of St. Croix, some of uncertain origin. *a*, Layer below hammer is entirely horizontally laminated and poorly graded. *b*, Series of superimposed, subtly graded layers. *c*, Large-scale low-angle lamination unlike typical C ripple bedform division of turbidites. Localities (Figure 2): *a* = site 43; *b* = site 44; *c* = site 45. Hammer is 28 cm long.

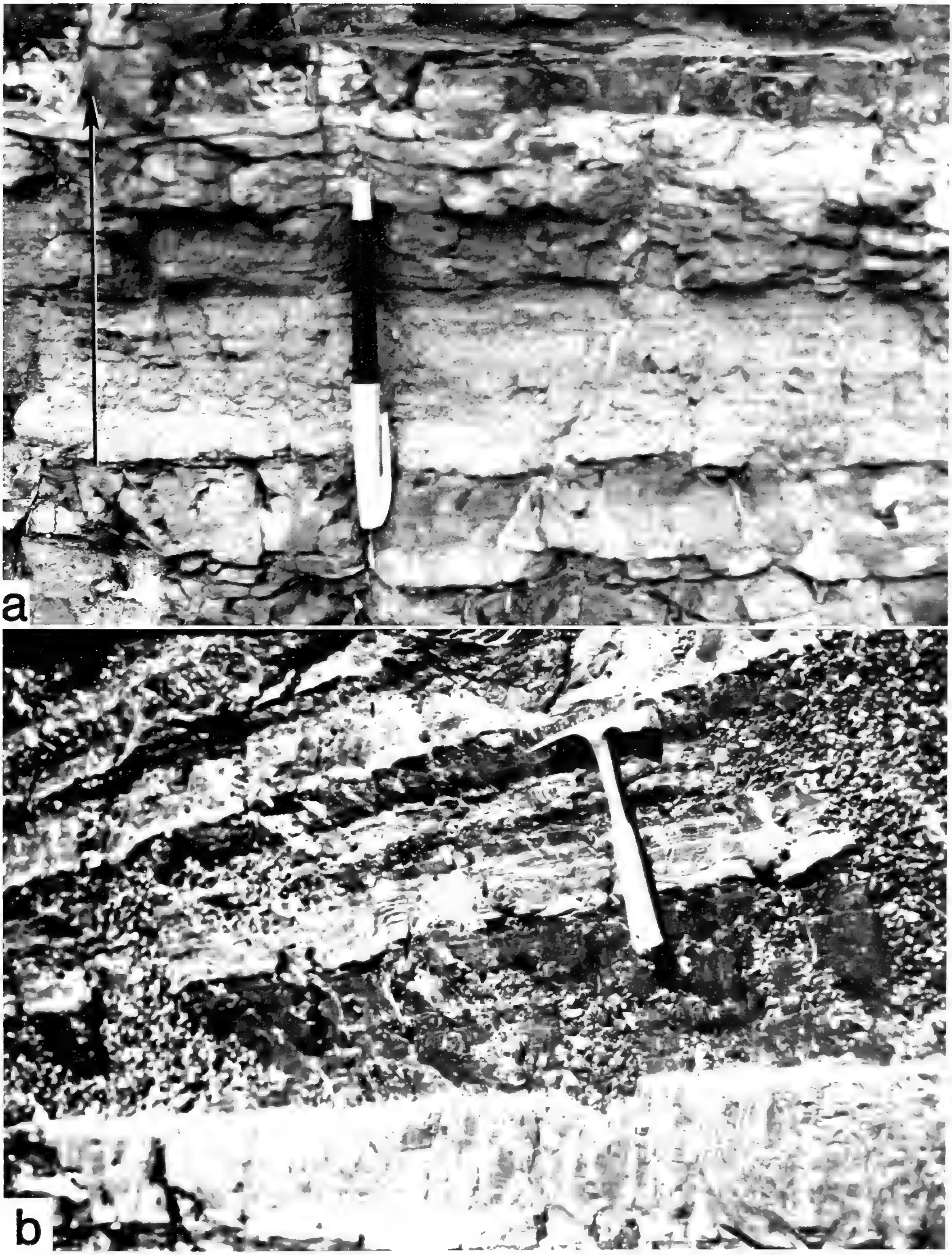

FIGURE 39.—Comparison of graded A–E sandstone turbidite (*a*, arrow) and B–E turbidite (*b*, stratum under hammer handle) with non-graded, sharp base-sharp top layer with poorly developed sequence of internal structures (20 cm-thick layer, at bottom of photo in *b*). Origin of this latter sandstone stratum remains undefined. Localities (Figure 2): *a* = site 17; *b* = site 3. Pen is 14 cm and hammer is 28 cm long.

and/or large-scale cross-bedding throughout much of the bed (Figure 38*c*). Extensive bioturbation, in some instances, can also thoroughly disrupt most or all of the original stratification. Such layers also tend to be discontinuous.

Thus, many sandstone layers appear markedly different from the more "exemplary" and "classic," but less frequent, sandy turbidites in the same stratigraphic section. Nevertheless, these sandstone layers preserve one or several sedimentary features (usually at the base or in the lower part of the bed) that strongly suggest that the sands were, at least initially, emplaced by turbidity-current flows. It would appear that the assemblage of physical and biogenic structures of these "anomalous" strata records the effects of some other transport process, i.e., one which most probably modified the turbidites *after* their initial deposition in lower-slope environments.

Bottom-Current Transport: A Subsequent Depositional Mode

CHARACTERISTICS OF TRACTIVE-CURRENT DEPOSITS ON ST. CROIX.—The bedforms and sedimentary structures of some sandstone layers in both Caledonia and Judith Fancy localities on St. Croix are sufficiently distinctive to propose transport largely by tractive processes rather than turbidity currents. Sandstone strata that appear deposited primarily by some form of fluid-driven mechanism—presumably bottom currents—comprise up to 20% of the sandy beds in some sections. It is of note that such sandy layers of probable tractive-current origin are found interspersed with turbidites in the same stratigraphic section. As will be discussed below, this recognition of two distinct depositional types preserved at the same locality is critical for reconstructing the sequence of events affecting the emplacement of the sandy strata on St. Croix.

The physical attributes of layers deposited by deep-marine tractive currents in modern oceans have been described and well illustrated by Heezen and Hollister (1971, chap. 9). The characteristics of bottom-current-transported, sandy deposits are also summarized and their attributes illustrated in other studies of modern ocean sediments (Hollister and Heezen, 1972; Bouma and Hollister, 1973; Stow and Lovell, 1979) and of ancient deep-sea sediments preserved in the rock record (Hsü, 1964; Bouma, 1973; Anketell and Lovell, 1976; Unrug, 1977, 1980; Stow and Shanmugan, 1980; Lovell and Stow, 1981; Friedman, 1984). It has been demonstrated that bottom water driven by thermohaline circulation in some parts of modern oceans can displace sediment as coarse as granules and coarse-grained sand. Moreover, such material can be displaced over large areas at bathyal or greater depths, particularly at the western boundaries of ocean basins (Hollister and Heezen, 1972). Tides and internal waves are additional components in sediment transport at depths below the shelf-break.

Most sandy layers interpreted as being emplaced primarily by bottom currents are thin, ranging from 0.5 to 10 cm, but usually less than 3 cm thick. Their geometry is diverse: moderately even-bedded and fairly continuous, or wavy bedded, or discontinuous (lenticular, ripple bedded). The vertical sequence of bedforms and textural attributes of sands emplaced primarily by fluid-driven circulation differs substantially from the thin-bedded turbidites discussed in the previous section. For example, instead of fining upward as in turbidites (Figure 39*a*) the bottom-current emplaced stratum is typically sharp topped as well as sharp-based (Figures 39*b*, 40–43), and typically foreset or cross laminated throughout most, if not all of the bed, i.e., from base to top (Figures 40–43). Lamination inclinations range from about 10° to 30°. The massive (A) and lower, distinct, horizontal-laminated (B) divisions associated with typical turbidites are usually absent at the base of the bottom-current, emplaced layer.

The sand in such tractive layers is somewhat finer-grained and better sorted, with a lower matrix content (Figure 42), than in some thin-bedded turbidites of comparable thickness with which they are interbedded. In thin section the grains are almost always in close contact with each other, and elongate particles are sometimes aligned. However, it is recalled here again that, as in the case of turbidites, the deposits in many sections have been markedly affected by low-grade metamorphism. It is expected that the original grain-to-grain and grain-to-matrix contact, and also the original grain orientation, have been modified, sometimes substantially, after deposition.

The upper stratal surface is usually sharp and may be flat (Figures 42*a–d, f*) or wavy and undulating (Figures 42*g*, 43, 44*a*, 45*b*). In cross-section some sandstone units as a whole show large-scale megaripple bedding (Figure 44*a*) or thick, superposed foresets (Figure 44*b*). Others show discontinuous bedding, including lens-like, "starved," rippled (Figure 45*a*), and pulsing-current (Figure 46*a*) configurations. Flaser bedding, with mud in ripple troughs and partly on crests (cf. Reineck and Singh, 1975, 97–99), is also noted in some polished sections (Figures 43*a*, 47*c*). Reverse-graded bedding is sometimes observed in polished slab and thin section (Figure 48*a–d*). Thin sections (Figure 42*b,d*) also reveal some cross-and foreset-lamination highlighted by heavy mineral concentrations (including apatite, enstatite, actinolite, and opaque minerals), and also by iron staining. This observation and others cited above suggest processes of placer concentration (Figure 47*a,c*) and winnowing of fines, typically associated with the development of ripples in an environment affected by bottom currents. Microprobe analysis of dark laminae shows that these are usually iron-enriched: this may be a post-depositional weathering phenomena, perhaps alteration of selected, iron-rich, heavy-mineral grains concentrated along lamination surfaces.

Bioturbation is an important attribute of the tractive deposits of Cretaceous formations in St. Croix. Reworking by organisms may be moderate or disrupt much, if not all, of a bed (Figures 49, 50) or even several closely-spaced strata.

In large outcrop sections, including the Springfield (Figure

FIGURE 40.—Sandy strata with sharp base and sharp top, displaying well-defined foreset lamination. Apparent current transport, shown by arrows, toward right in *a* and toward left in *b*. Localities (Figure 2): *a* = site 18; *b* = site 19. Hammer is 28 cm and pen is 15 cm long.

FIGURE 41.—Current laminated sandy strata, with sharp flat base but wavy upper surface. Apparent current transport, shown by arrows, toward right in *a* and toward left in *b* and *c*. Dark laminae in *c* highlighted by concentrations of heavy minerals. Localities (Figure 2): *a* = site 7; *b* = site 57; *c* = site 55. Pen is 13 cm and hammer is 28 cm long.

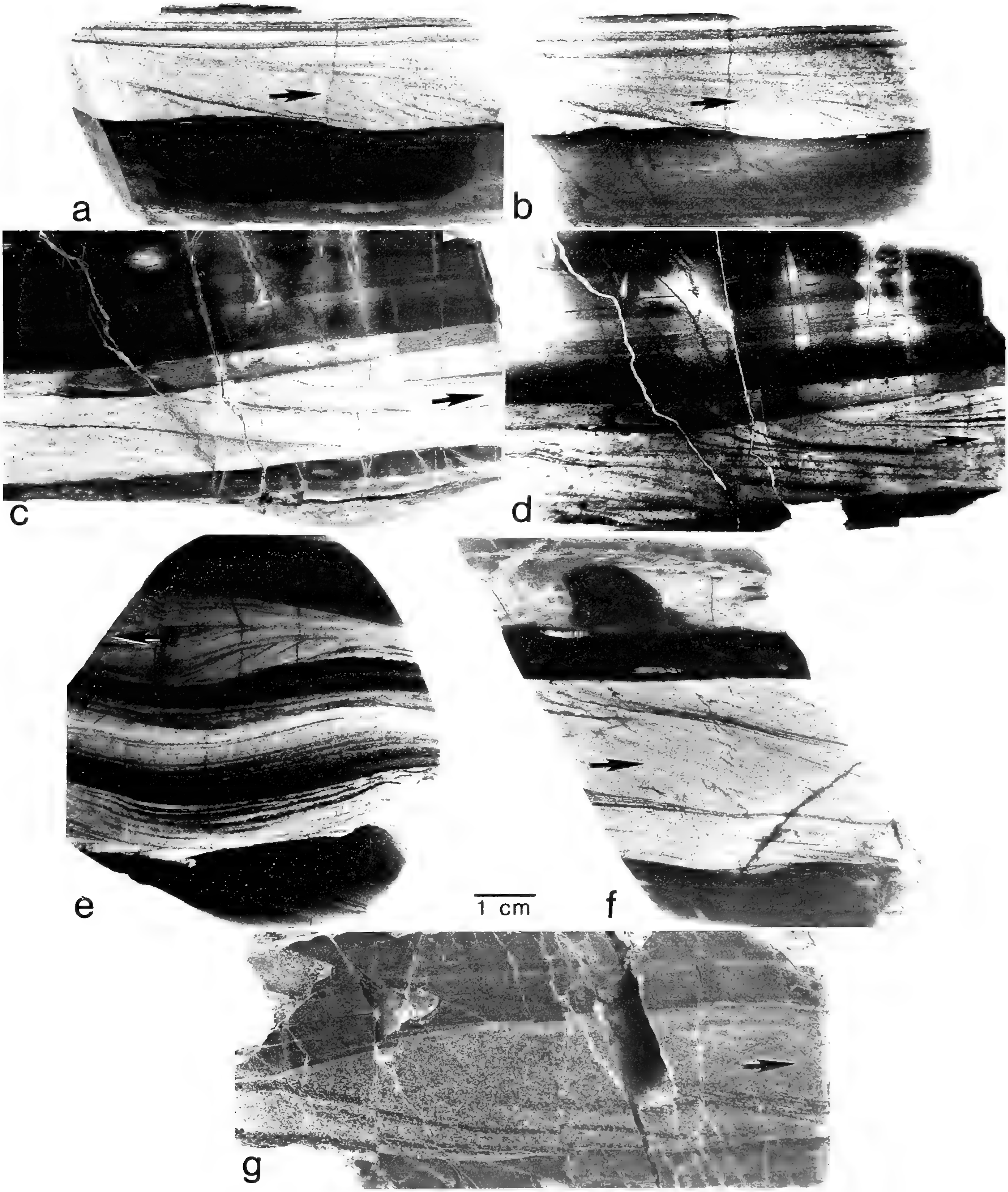

FIGURE 42.—Polished sections (*a,c,e–g*) and thin sections (*b,d*) showing non-graded sandy strata with sharp base and top. Foreset lamination (arrows indicate apparent current directions); some laminae highlighted by heavy minerals (*a–d*). Note lens-shaped ripple-bedded stratum in *g*. Localities (Figure 2): *a–d* = site 22; *e* = site 21; *f* = site 50; *g* = site 19. Scale bar applies to all components.

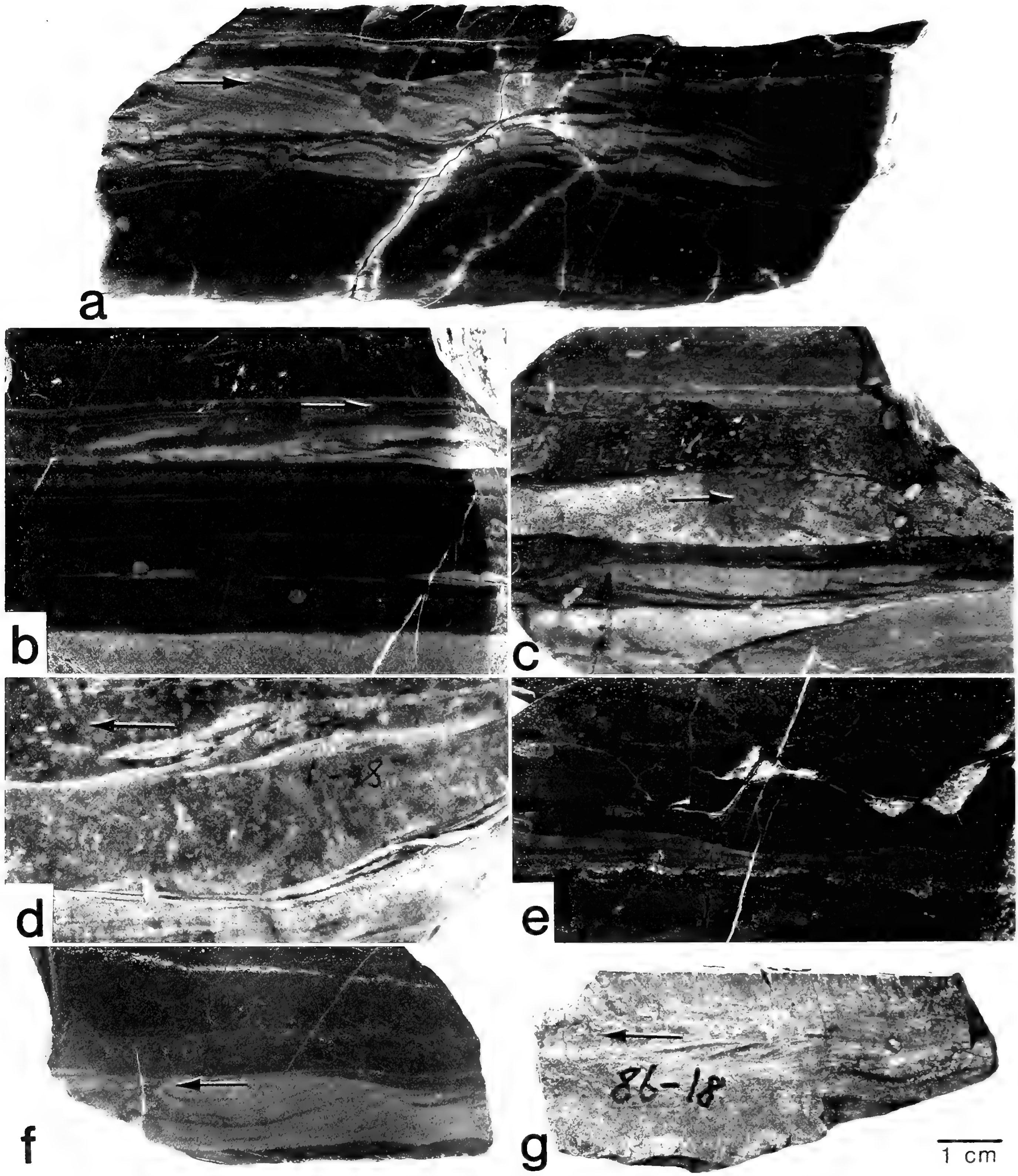

FIGURE 43.—Thin, current-laminated, sandy layers displaying wavy and discontinuous bedding. Apparent current directions shown by arrows. Note flaser-like bedding in *a* and diverse, rippled- bedform configuration of layer in *b* to *e*. Localities (Figure 2): *a,f* = site 57; *b,e* = site 55; *c* = site 44; *d* = site 56; *g* = site 10. Scale bar applies to all components.

FIGURE 44.—Megaripple bedform (crest-to-crest distance about 1 m) in *a* and thick overlapping foresets in *b*. Both exposures at Manchenil Bay Point (site 7, Figure 2). Apparent direction of transport toward right in both examples (arrows). Pen is 13 cm and hammer is 28 cm long.

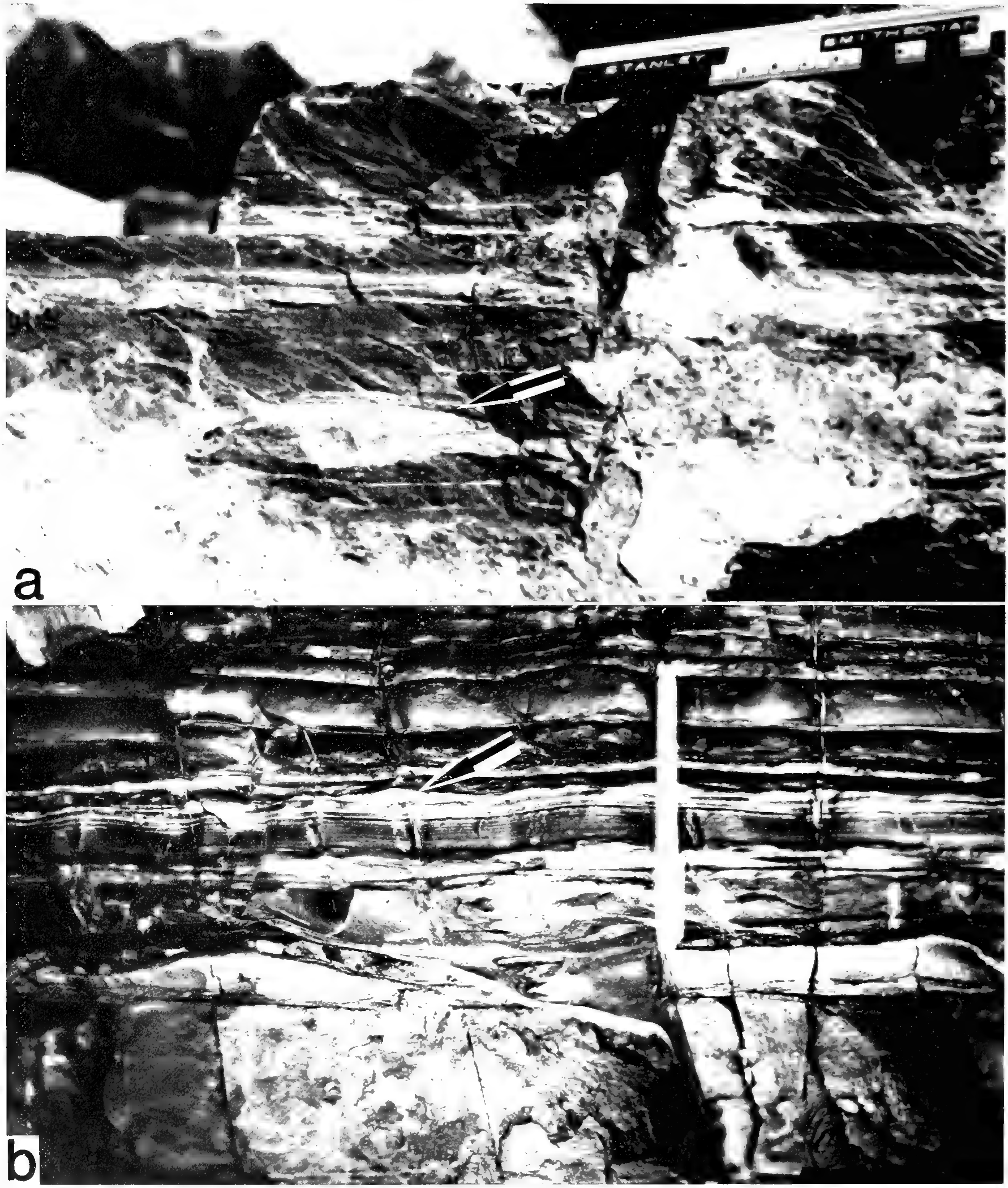

FIGURE 45.—Thin sandy layers, some discontinuous and lens-like (arrow in *a*, with apparent current transport toward left), and others lenticular and wavy bedded (arrow in *b*). Stratigraphic sections in *a* and *b* include both bottom-current/tractive transport and turbidite layers. Localities (Figure 2): *a* = site 57; *b* = site 20. Centimeter scale in *a* and pen is 14 cm long in *b*.

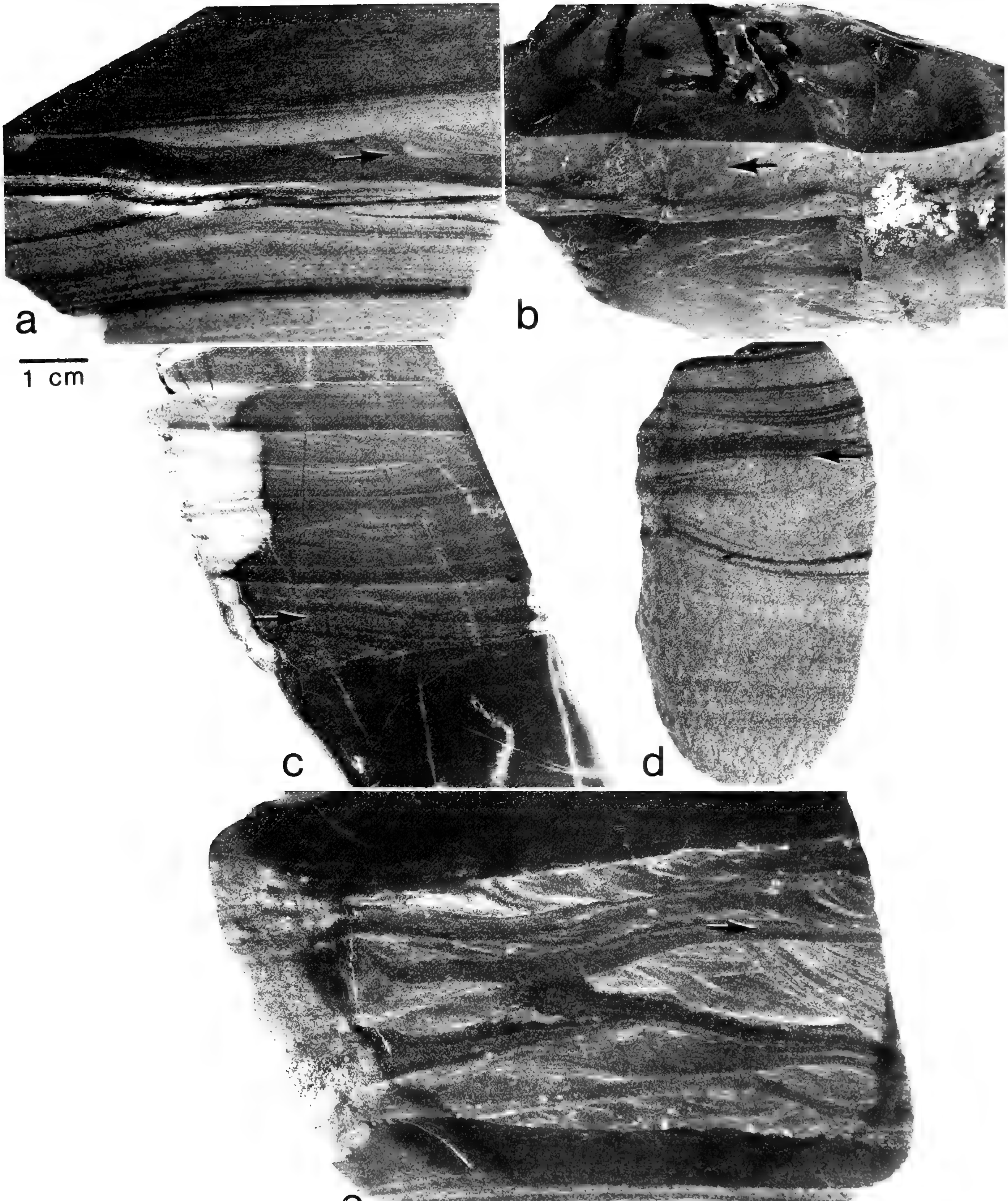

FIGURE 46.—Polished sections of sandy laminated (some cross-bedded) sections showing wavy and rippled configurations. Apparent transport directions indicated by small arrows. Localities (Figure 2): *a,e* = site 50; *b* = site 52; *c* = site 20; *d* = site 18. Scale bar applies to all components.

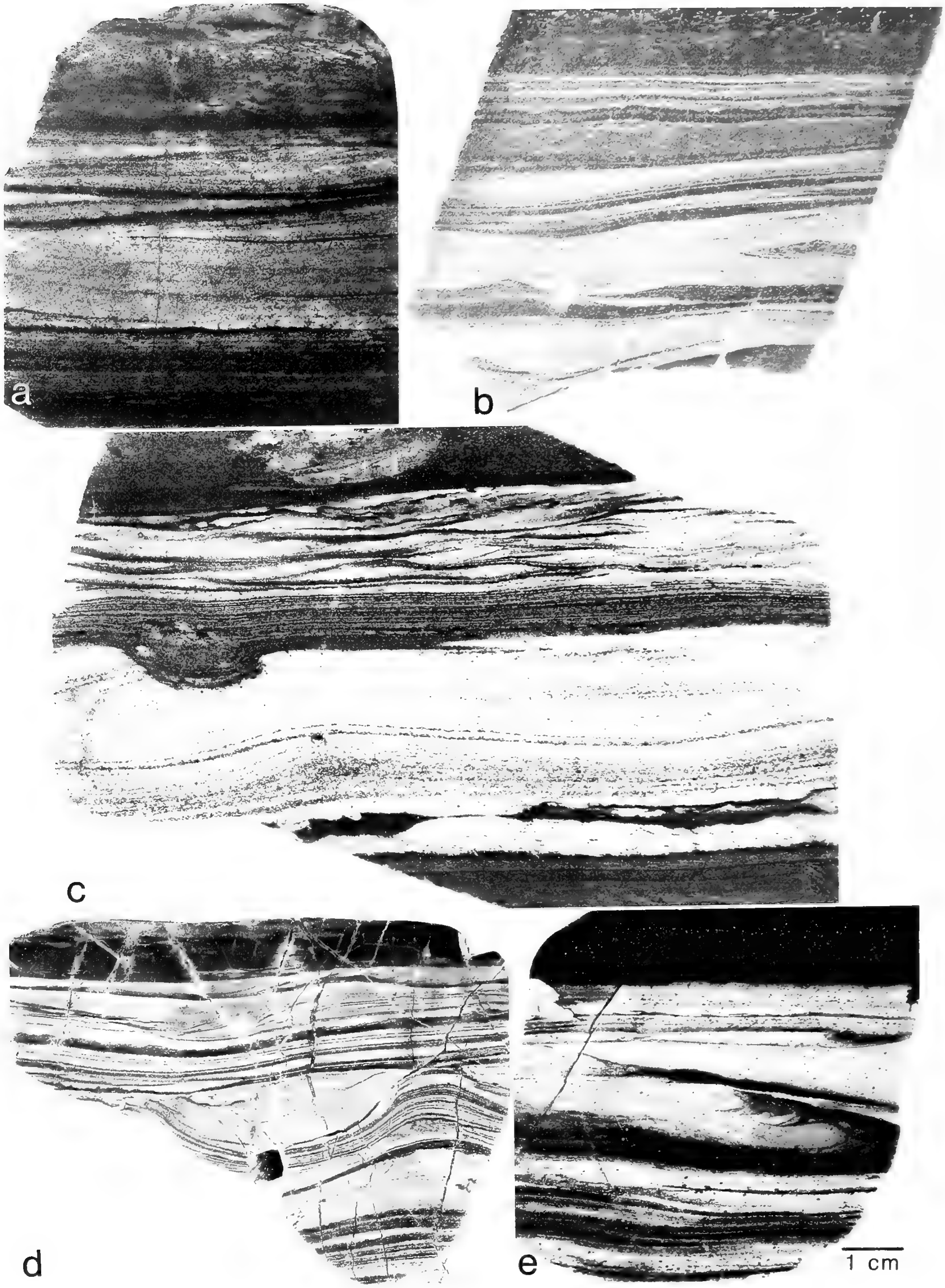

FIGURE 47.—Polished sections of current-laminated strata, some showing flaser-like structures (upper in C). Dark laminations in these selected non-graded samples highlighted by heavy minerals (*a*, lower in *c*) and also by fine-grained sediments (*b,d,e,*). Localities (Figure 2): *a* = site 18; *b,c,e* = site 50; *d* = site 2. Scale bar applies to all components.

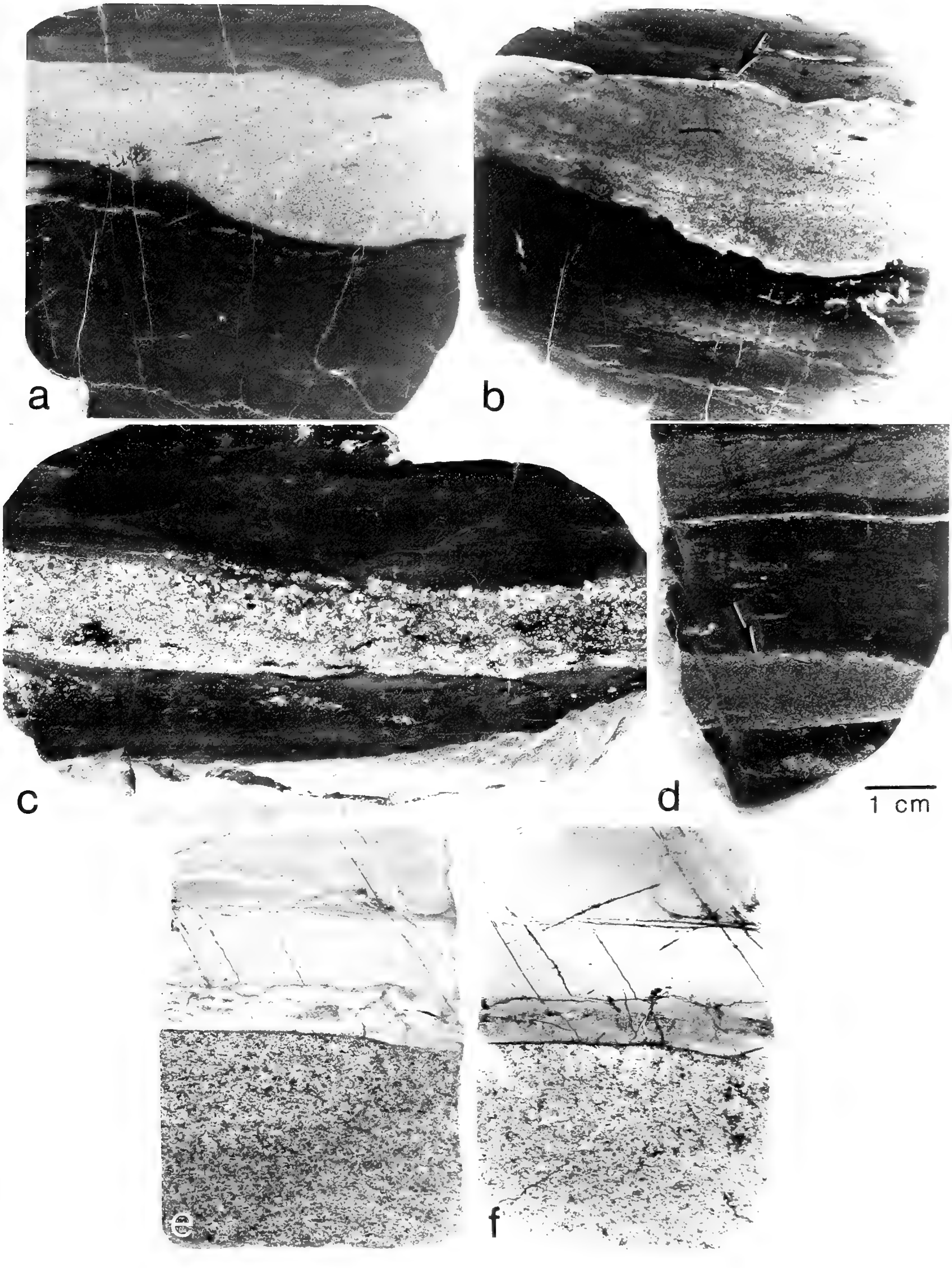

FIGURE 48.—Polished (*a*, *c–e*) and thin sections (*b*, *f*) showing non-graded (*e,f*) and reverse-graded bedding (in *b–d*). Note rippled bedform in *a,b*, and lenticular configuration in *d*. Localities (Figure 2): *a,b* = site 21; *c* = site 50; *d* = site 53; *e* = site 14. Scale bar applies to all components.

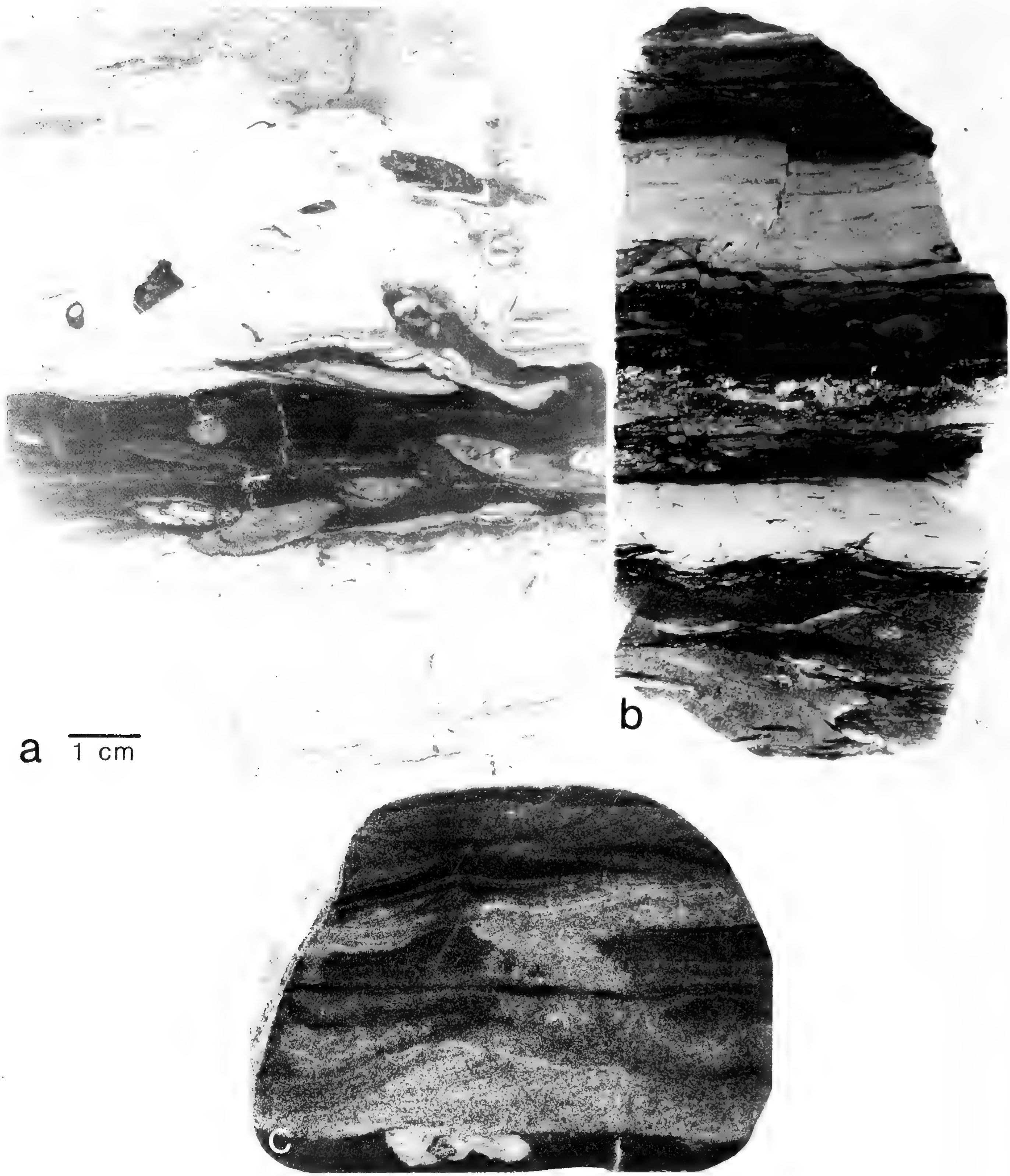

FIGURE 49.—Polished sections illustrating diverse examples of bioturbation noted in bottom-current transported, including rippled, layers (*c*). Reworking by organisms involves both sandy and mud-rich layers. Localities (Figure 2): *a* = site 55; *b* = site 16; *c* = site 50. Scale bar applies to all components.

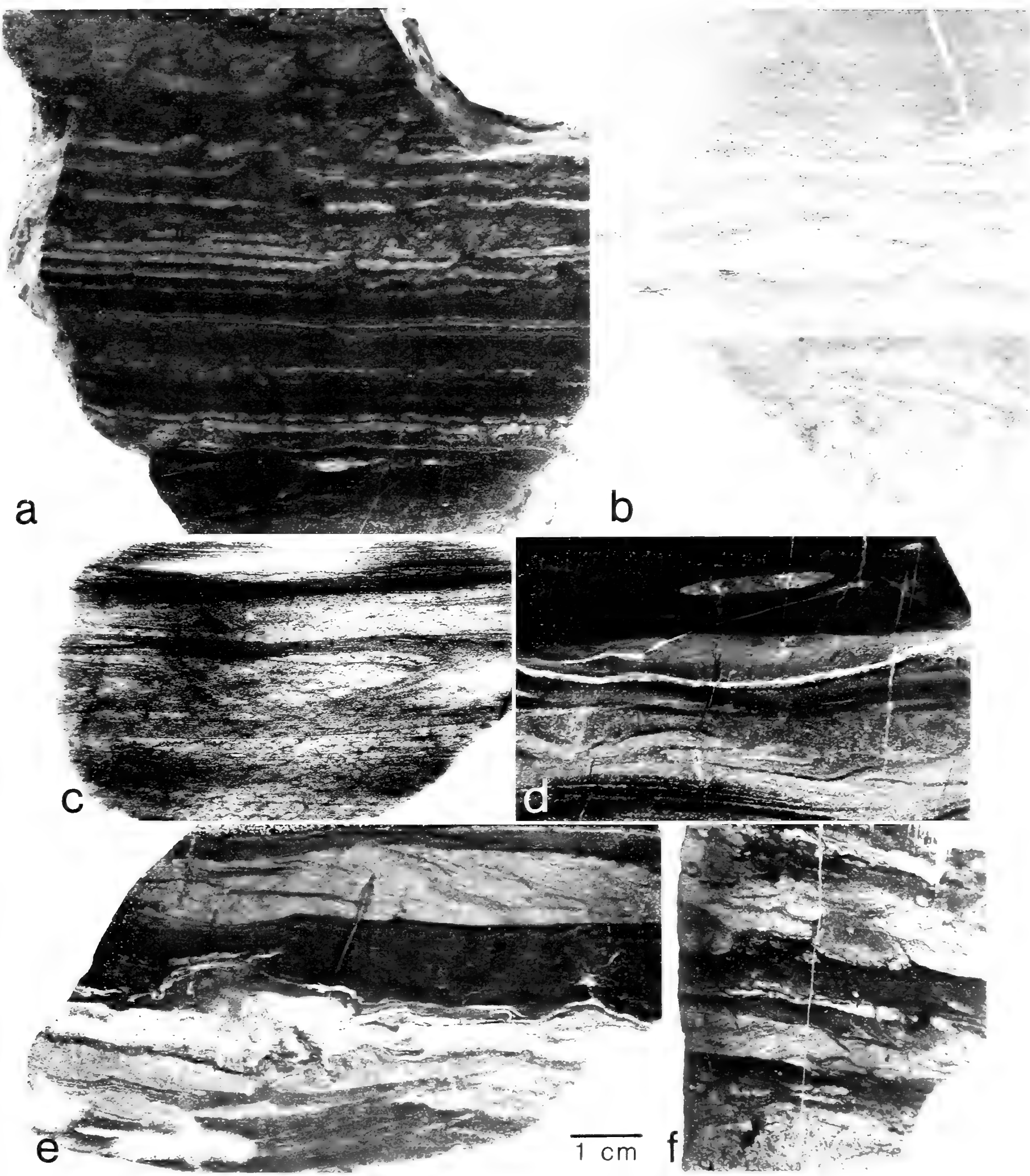

FIGURE 50.—Polished sections illustrating diverse examples of bioturbation noted in bottom-current transported, including rippled, layers such as *b*. Note complete disruption of stratification in some sandy layers (lower part in *a*, and *e*). Localities (Figure 2): *a* = site 55; *b* = site 50; *c* = site 21; *d* = site 1; *e* = site 43; *f* = site 53. Scale bar applies to all components.

FIGURE 51.—A well-exposed ripple-train surface showing weakly undulating-to-straight crested ripples in fine-grained sandstone in Springfield Crusher quarry (site 57, Figure 2). Current direction, toward upper left, shown by arrows. Section in *a* is close-up of large surface shown in *b*. Hammer is 28 cm long.

51*b*), the St. Croix Sand and Stone, and the Caledonia Gut quarries, the well-exposed upper surface of some beds is entirely rippled. These surfaces covered by ripple trains display several types of ripple forms. The most common are weakly undulatory to straight-crested (Figure 51*a*), asymmetric in profile. Ripples superimposed on larger mega-ripples (Figure 44*a*) are also observed on a more restricted scale (Manchenil Point, site 7, Figure 2).

PALEOCURRENT ANALYSIS.—The paleocurrent measurements determined from rippled bedding surfaces and foreset lamination in both eastern and western St. Croix and on Buck Island indicate regional trends in tractive transport, primarily toward the WNW, W, and WSW quadrants. The directions at any one site, however, are usually not uniform, a phenomenon also noted by Whetten (1966b:195). For example, tractive-current structures in the Caledonia rocks at Point Cudejarre and East End Point (sites 18 and 19, Figure 2), and in the Judith Fancy sequence at Manchenil Bay (site 7, Figure 2), indicate transport toward both the NW and the SE (Figure 5).

The exact orientation of the above-cited paleocurrent trends during the Late Cretaceous may be compromised by the intense, post-depositional, structural activity that has deformed the Cretaceous series. However, the overall regional westerly direction of tractive transport recorded by different Cretaceous rock units at diverse localities, all of which have been tectonically modified, is sufficiently consistent to allow the generalized east-to-west interpretation proposed herein.

Interestingly, it appears that in some Caledonia and Judith

Fancy sections the major tractive-current transport trends (primarily toward the W) are oriented in a direction perpendicular to that measured on turbidites (primarily N-S trends). That paleocurrent trends measured from bottom-current structures are oriented in directions that are normal, or at a considerable angle, to those of sediment-gravity flows (presumably oriented downslope) at the same locality (Figure 5) provides a powerful argument favoring contour-following tractive flow. Neither the mechanism(s) inducing such bottom currents in this region nor the precise orientation or intensity of their flow are known. From the sum of observations, however, it is clearly apparent that the currents sweeping the ocean floor were sufficiently powerful to displace fine- to coarse-grade sand along the lower-slope environments.

Bottom Currents and the Reworking of Turbidites

CHARACTERISTICS OF SANDY VARIANT LAYERS ON ST. CROIX.—The assemblage of sedimentary structures discussed in the previous section indicates that the flow of water above the bottom was sufficiently strong to displace coarse sand and granules and thus was able to rework and redeposit volcaniclastic sand layers. It is these currents that have resulted in the lithofacies variants that are transitional between typical turbidite and distinct, bottom-current deposited end-members. These, herein, are termed variant layers. This section focuses on these sandy turbidite-tractive current variants that are observed in both the Caledonia and Judith Fancy formations and constitute the dominant lithofacies in these Cretaceous series.

Most stratigraphic sections on St. Croix include some distinct, well-graded, sandstone turbidites (see the lower bed in Figure 52*a*). Most of these sections, however, usually comprise substantially more strata that display stratification characteristics different than classic turbidites. Many of these variant units, for example, display a bedform geometry that is wedge-shaped or wavy-ripple bedded (strata in the middle and top part of Figure 52*a*, and in the upper part of Figure 52*b*) rather than evenly stratified. Moreover, foreset lamination is usually pronounced throughout most of the bed, usually occurring just above a thin, generally much-reduced, basal-graded horizon. Confusion in identification of lithofacies usually arises because variants often show some upward-fining at or near their base. As in the case of typical turbidites, the base of this lower-graded portion is usually sharply defined and displays an erosional contact with the underlying mudstone (Figure 52*b,c*).

At the same outcrop it is sometimes difficult to distinguish a thin sand A–E turbidite with a well-developed foreset-laminated C division (Figure 53*a*) from a thin sandy variant layer where the basal-graded massive A division passes directly to a laminated section similar to the C division of turbidites (Figure 53*b*). Careful inspection shows that the basal-graded unit is delimited by a sharp upper stratification contact that sometimes forms a wavy rippled surface; directly above this contact lies the foreset-laminated unit (Figure 53*b*). This contact is interpreted as a break in sedimentation wherein currents depositing the upper layers have eroded and/or reworked the turbidite layers remnant in the lower bed. In sandy variants, the planar horizontal-laminated division B, usually found above the graded A term of turbidites, is notably absent (Figures 53*b*, 54*a,b*). Moreover, in some of these sandy layers, the lower-graded portion is topped by a foreset- and cross-laminated section where the laminae are highlighted by heavy-mineral concentrations (Figures 54*c,d*, 55*b*).

INTERPRETING THE DEPOSITIONAL ORIGIN OF VARIANTS.—Thus, in most cases it is the lower part of sandy variants that is most closely similar to that of thin sandstone turbidites: (1) a graded-basal unit (usually sand plus matrix) may be present; (2) the sharp base frequently shows an erosional contact with the underlying mudstone, and (3) the base of bed also commonly displays what appear to be load-deformed sole markings (Figures 54*c*, 55*b*) and flame structures (Figures 56*c*, 57*a*). In contrast with turbidites, however, is the absence of a planar division and upward passage from the graded-bedding layer directly to the laminated rippled section (Figures 56*a,d,e*, 57*g*) consisting of texturally cleaner sand. This upward sequence of bedforms provides an essential clue to interpret the origin of the variants: the foreset and cross lamination indicate a partial reworking by tractive processes of the sands forming the upper and middle parts of original turbidite layers. Tractive processes progressively erode a sand layer from the top downward. This downward reworking of the sand would thus best explain the disrupted (sometimes reversed) normal base-to-top sequence of turbidite bedform divisions.

The truncation of laminae at the upper bedding surface of sand layers (Figures 55*b*, 56*c*, 57*b–d, f*), recording erosion of rippled sand layers, provides additional evidence of bottom current processes. Other indications of such processes are the concentration of heavy minerals along lamination surfaces (Figures 56*d*, 57*b–d*), and the presence of flaser-type stratification (Figure 58*a,d*). All the above characteristics, together, attest to the extensive reworking of sand layers, including winnowing by bottom currents and deposition of placer deposits. If the tractive process is allowed to continue, all of the sand grains forming an original turbidite would be displaced and the original layer completely reworked. The end-product lithofacies should then resemble the bottom-current remolded deposits described in the previous section.

BIOTURBATION AND ITS SIGNIFICANCE.—It is of note that thin sandy layers recognized as anomalous turbidites, or variants, like many strata emplaced almost entirely by tractive processes, are commonly bioturbated. In those infrequent cases where bedding surfaces are exposed, burrows and grazing structures are sometimes observed (Figure 59*a*). In cross-section, layers reveal structures produced by benthic organisms that may be vertically oriented (Figure 60*a–c*). The activity of organisms is such that original internal stratification features can be

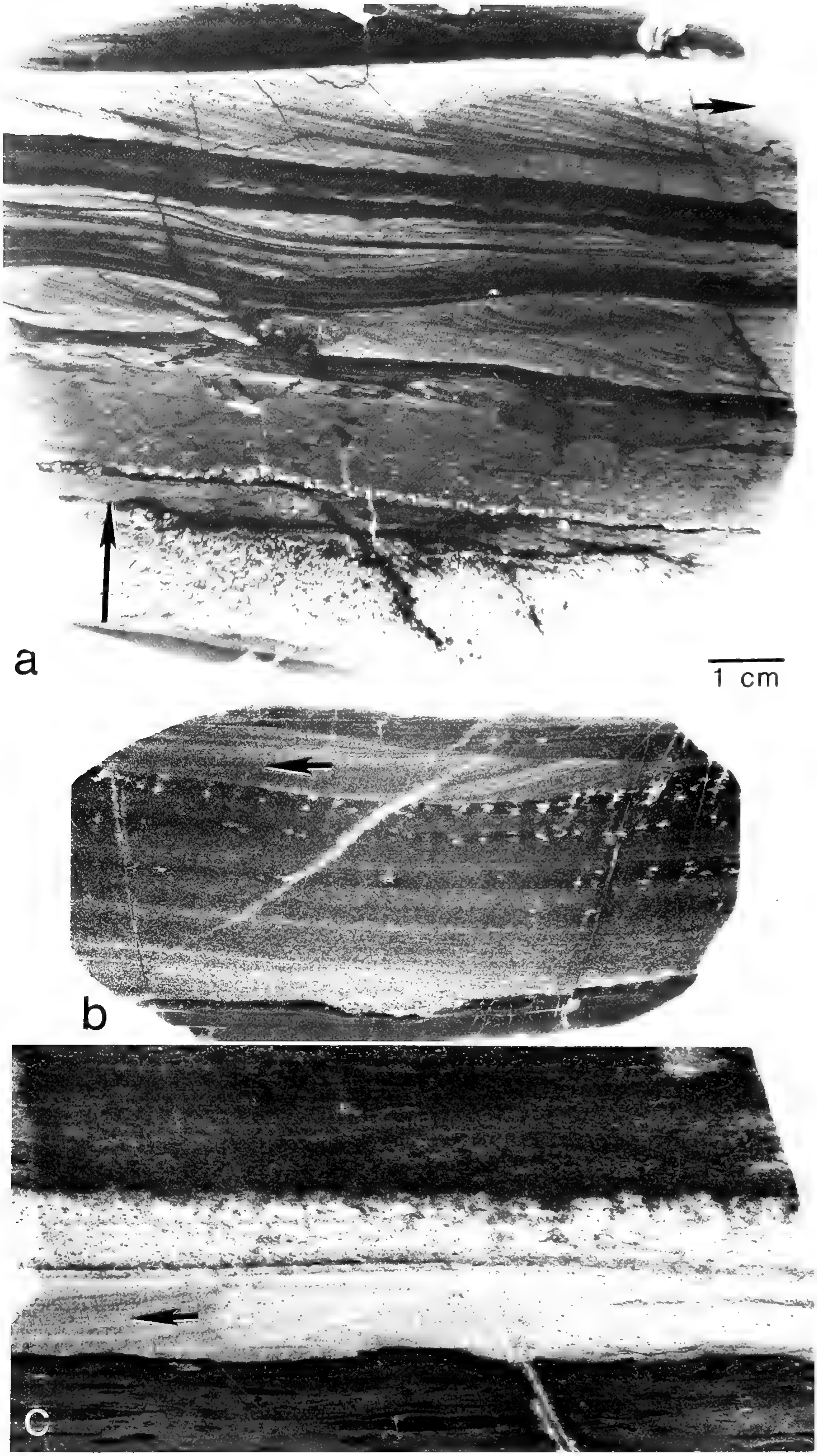

FIGURE 52.—Polished sections showing examples of diverse sandy strata in Caledonia Formation. Thin-bedded, graded, sandy turbidites (lower stratum in *a;* arrow shows upward fining) interbedded with non-graded, largely laminated layers. Note foreset, laminated, wavy- and lenticular-rippled layers in *a* and *b*, wedge-shaped layer (top in *a*), and sharp-topped and sharp-based, even-bedded layer in *c*. Localities (Figure 2): *a,c* site 50; *b* = site 3. Scale bar applies to all components.

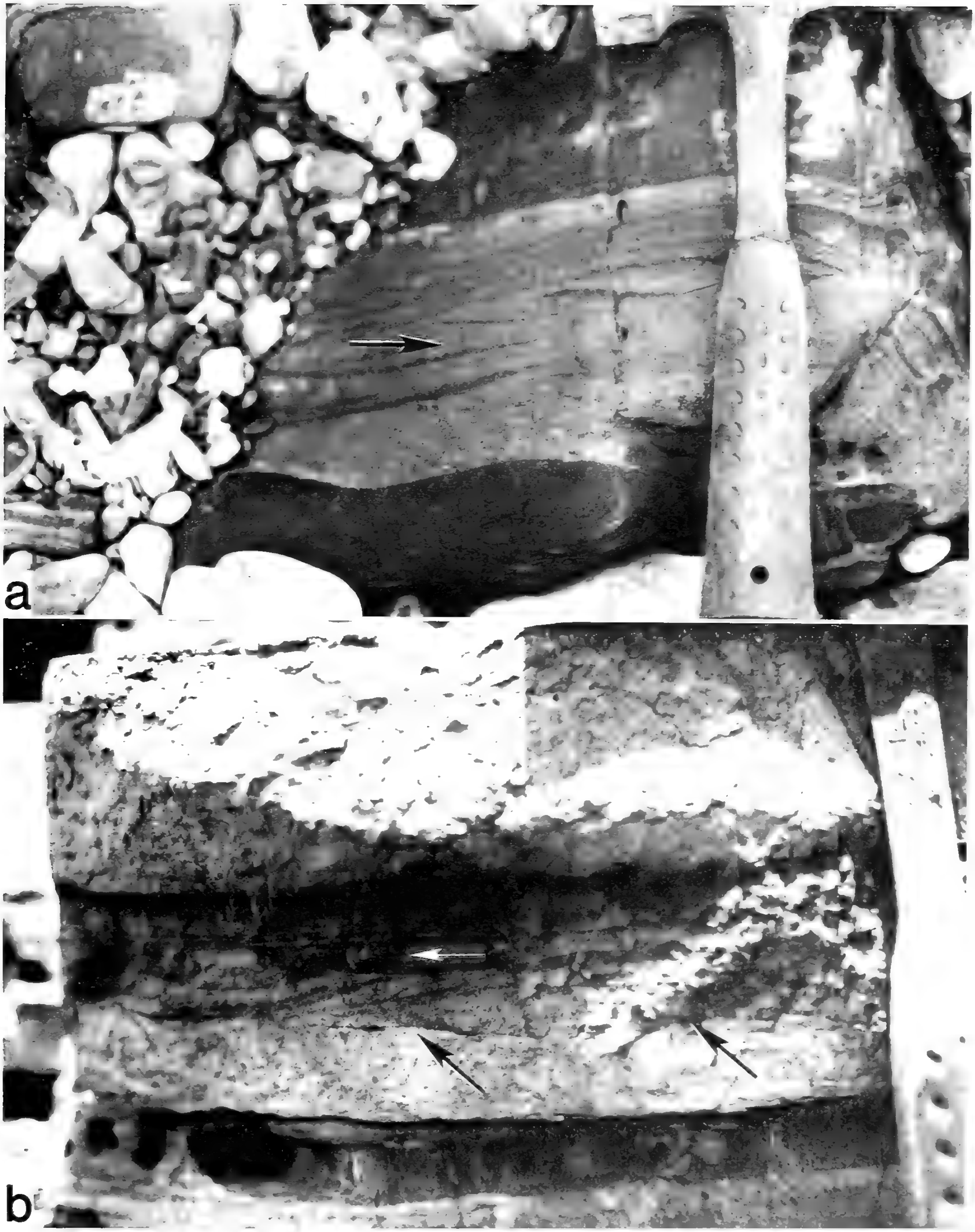

FIGURE 53.—Two sandy layers of about same thickness, each with basal massive and upper foreset and parallel laminated units, but probably of different origin. *a*, Sharp-based, well-graded, sandy turbidite showing upward progression of A, B, and C divisions; apparent transport direction toward right (arrow). *b*, Sandy sharp-based layer, with lower, poorly graded (perhaps massive A) division topped by rippled upper surface (two large arrows). This surface directly covered by sharp-topped, foreset-laminated unit (apparent transport direction toward left, small arrow), and in turn topped by separate, horizontal, laminated section. Rippling of basal layer and absence of lower B division below foreset laminated section should be noted. This layer interpreted as turbidite reworked by tractive current-transport. Localities (Figure 2): *a* = site 50; *b* = site 18. Hammer handle width is 3.5 cm.

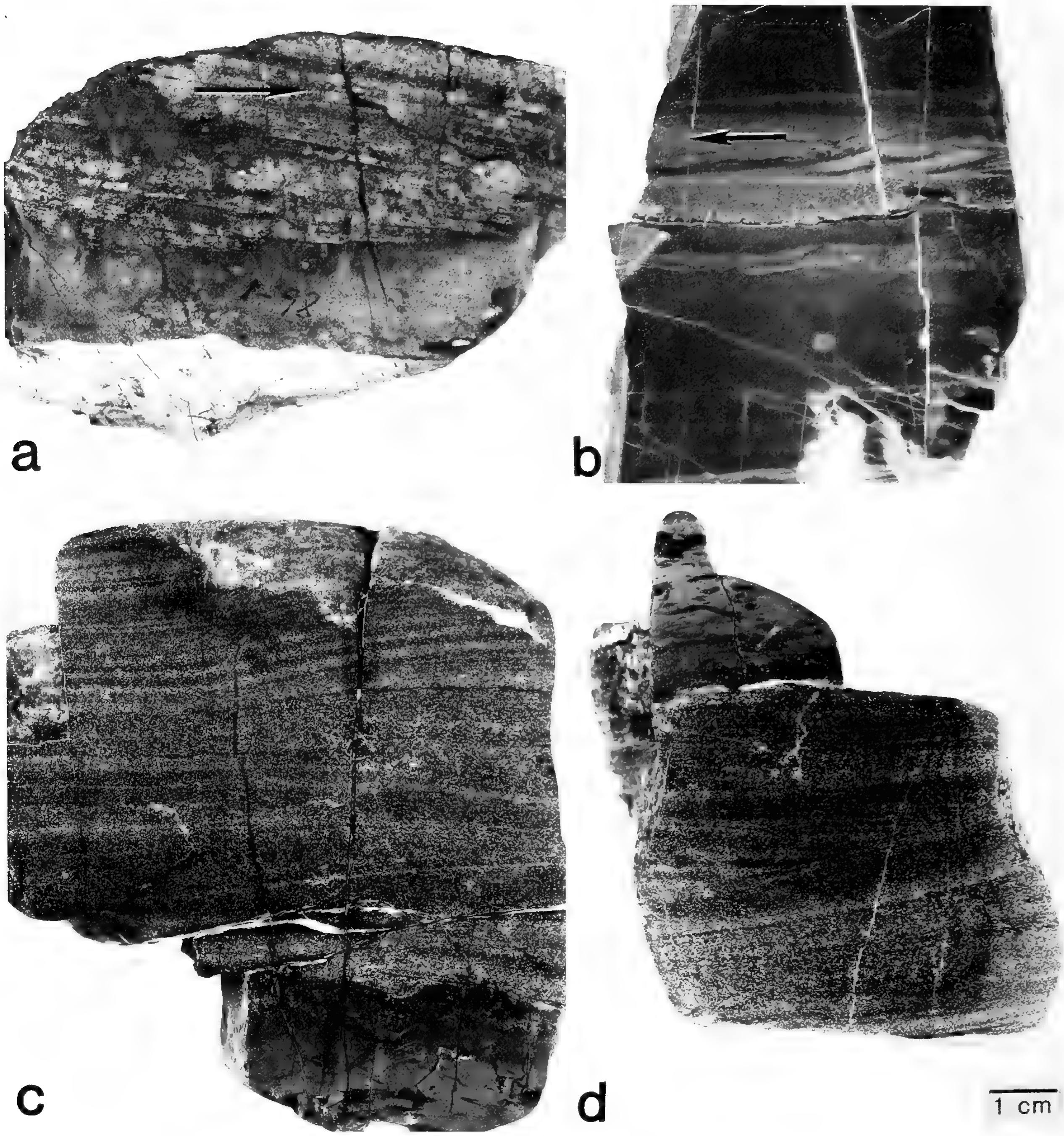

FIGURE 54.—Polished sections illustrating sandy layers that lack planar horizontal B division between graded base and upper foreset (*a,b*) or cross-laminated (*d*) part of stratum. Note marked erosional base in *a* and *c*. Apparent transport directions indicated by arrows. Localities (Figure 2): *a* = site 15; *b* = site 55; *c,d* = site 7. Scale bar applies to all components.

substantially disrupted and, in some cases, obliterated (Figures 59*b*, 60*d*). Bioturbation of fine-grained deposits is difficult to observe in the field but more readily apparent in polished sections (Figure 61). The sections indicate that reworking of the sea-floor surface by organisms was not restricted to sandy layers. Direct visual study of the seafloor shows that in some modern oceans bioturbation is intense and may occur rapidly, even at great depths. If observations made in modern settings are applicable to the Cretaceous rocks on St. Croix it would appear that there was ample time for benthic organisms to

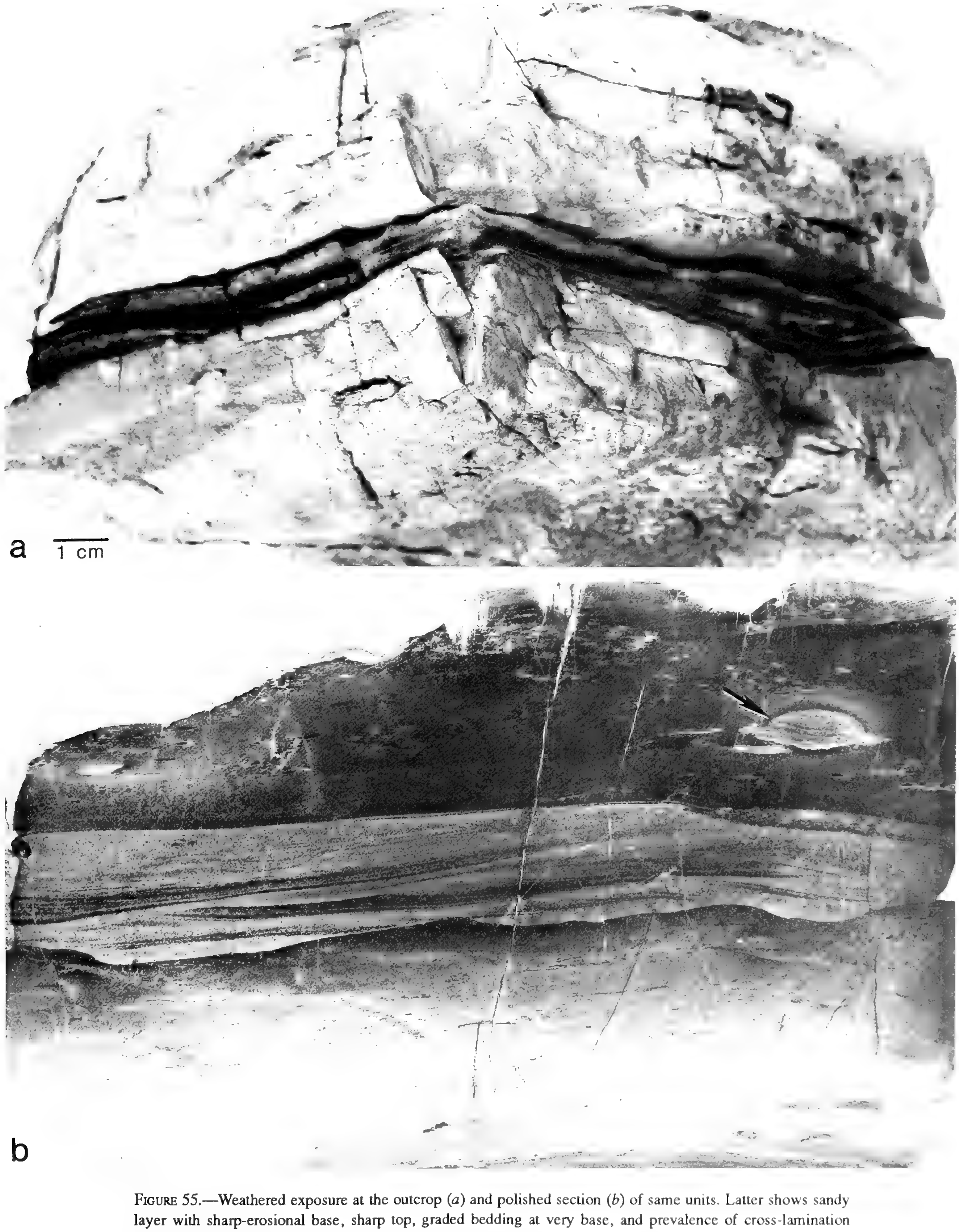

FIGURE 55.—Weathered exposure at the outcrop (*a*) and polished section (*b*) of same units. Latter shows sandy layer with sharp-erosional base, sharp top, graded bedding at very base, and prevalence of cross-lamination through stratum. Sandy lens (arrow) within finer-grained layer in (*b*) probably not biogenic in origin (laminae are preserved). Sample collected at East End Point (site 19, Figure 2). Scale bar applies to all components.

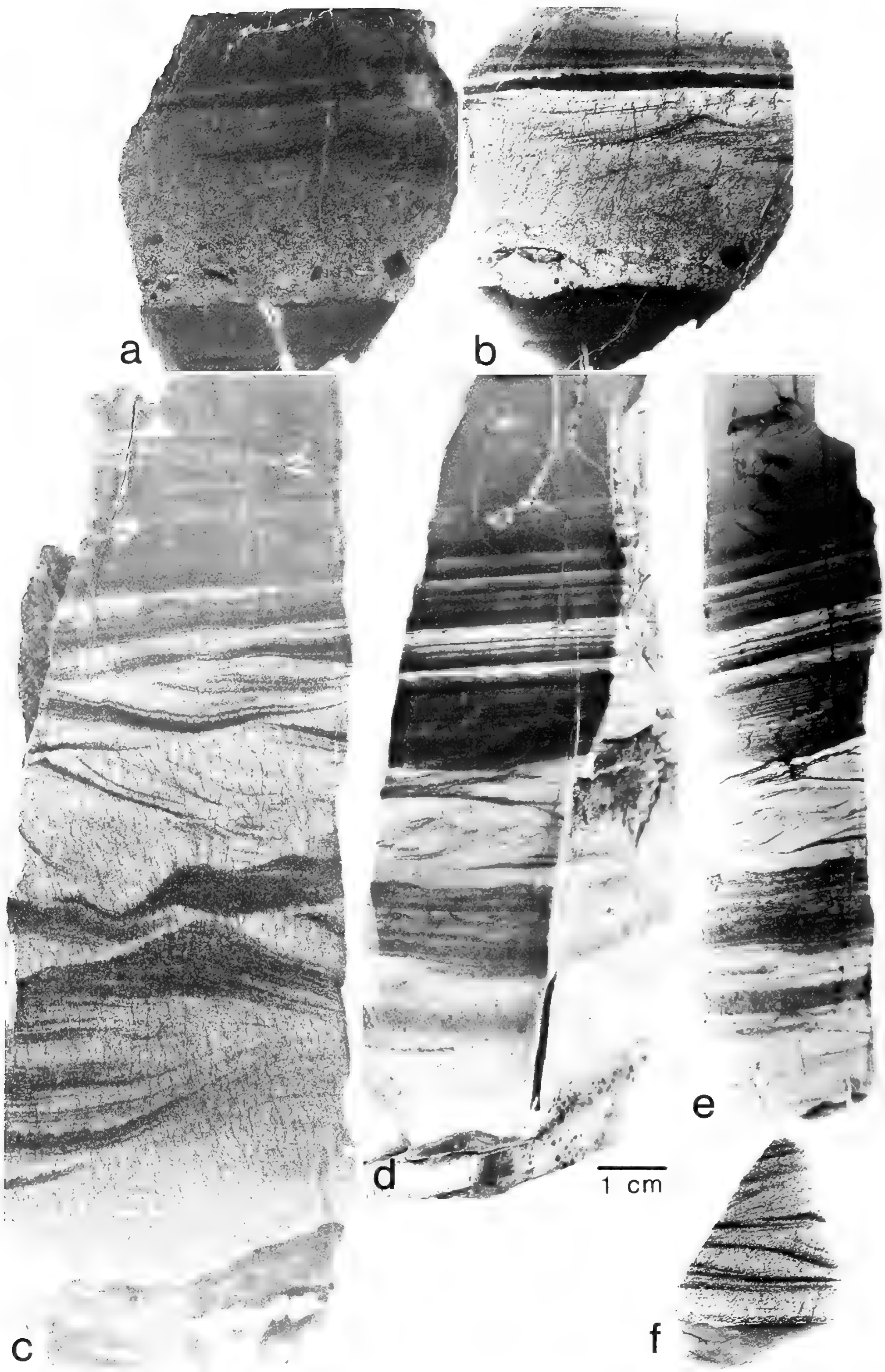

FIGURE 56.—Examples of sharp-based and sharp-topped, graded and laminated layers suggesting multiple depositional origin. *a,c,e* are polished sections; *b,d,f* are thin sections. *a,b,* Graded layer (A division) not followed upward by horizontally layered B division; note, however, upper rippled bedform and sharp top. *c–f* = Graded layers with erosional base (note small flame structures), and cross stratified throughout; some dark laminations (in *d* and *f*) highlighted by concentrations of heavy minerals. Localities (Figure 2): *a–c* = site 18; *d,e* = site 19; *f* = site 52. Scale bar applies to all components.

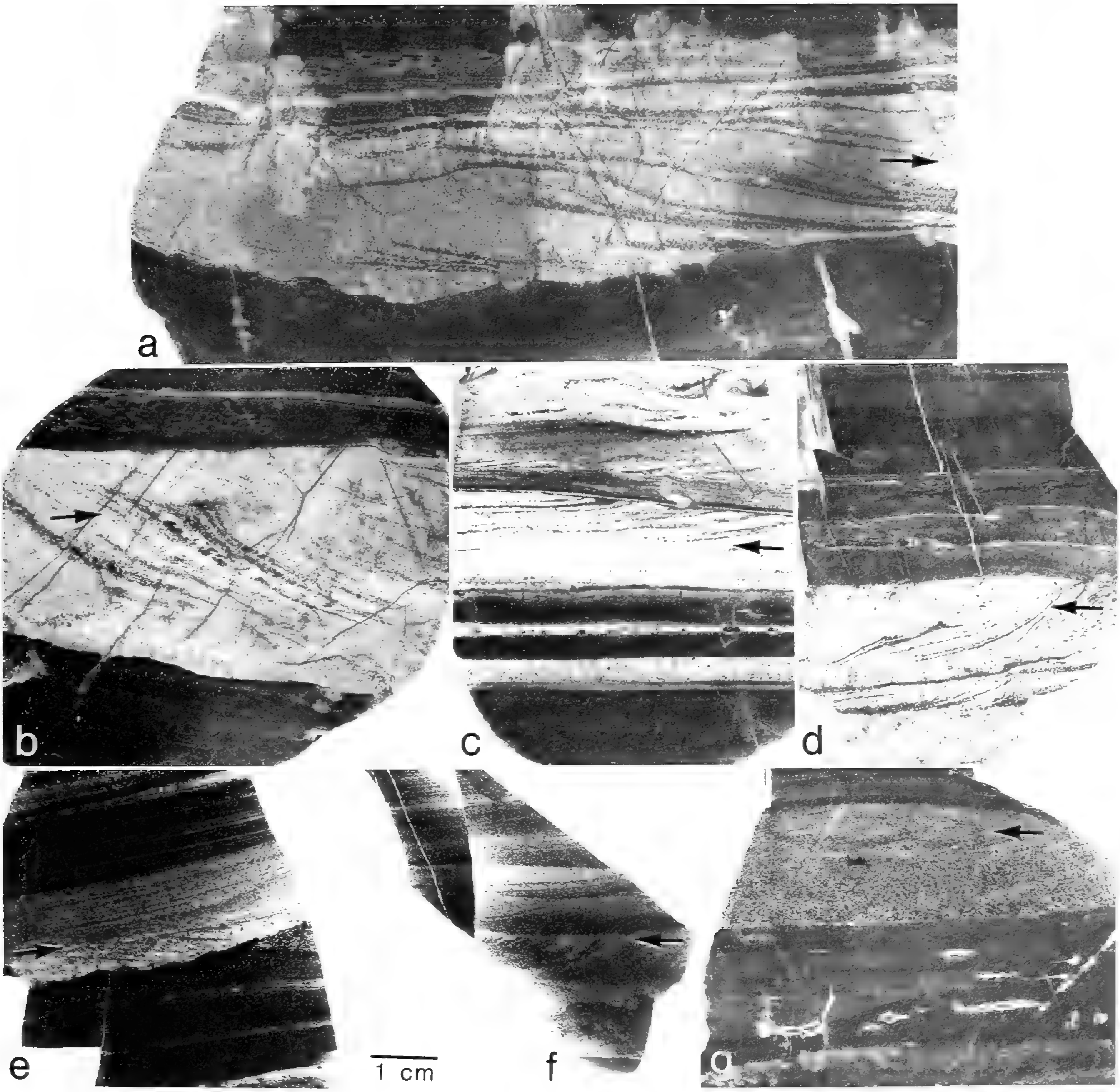

FIGURE 57.—Polished sections showing examples of thin, sharp-based (some with an erosional surface), and sharp-topped layers; some display moderate graded bedding at base. Upper foreset laminations may be truncated (particularly *b–d, f*); small arrows indicate apparent direction of transport. Foreset laminations can extend from (or near) top to base of bed. In several cases, laminations are highlighted by heavy mineral concentrations (*b,c*). Geometry of such strata is diverse: wavy bedded (*a*), wedge-like (*c*) or lenticular (*g*). Localities (Figure 2): *a,c,e* = site 50; *b* = site 43; *d* = site 17; *f* = site 52; *g* = site 18. Scale bar applies to all components.

rework and thoroughly disrupt the surficial sediment layers between the periodic incursions of sand emplaced by turbidity currents.

The generally good preservation of layering is probably a function of continuous sedimentation and relatively high rates of accumulation rather than a low benthic population or changes in the assemblages of organisms. Thus, it would appear that the pulses of sediment supplied to the lower slope

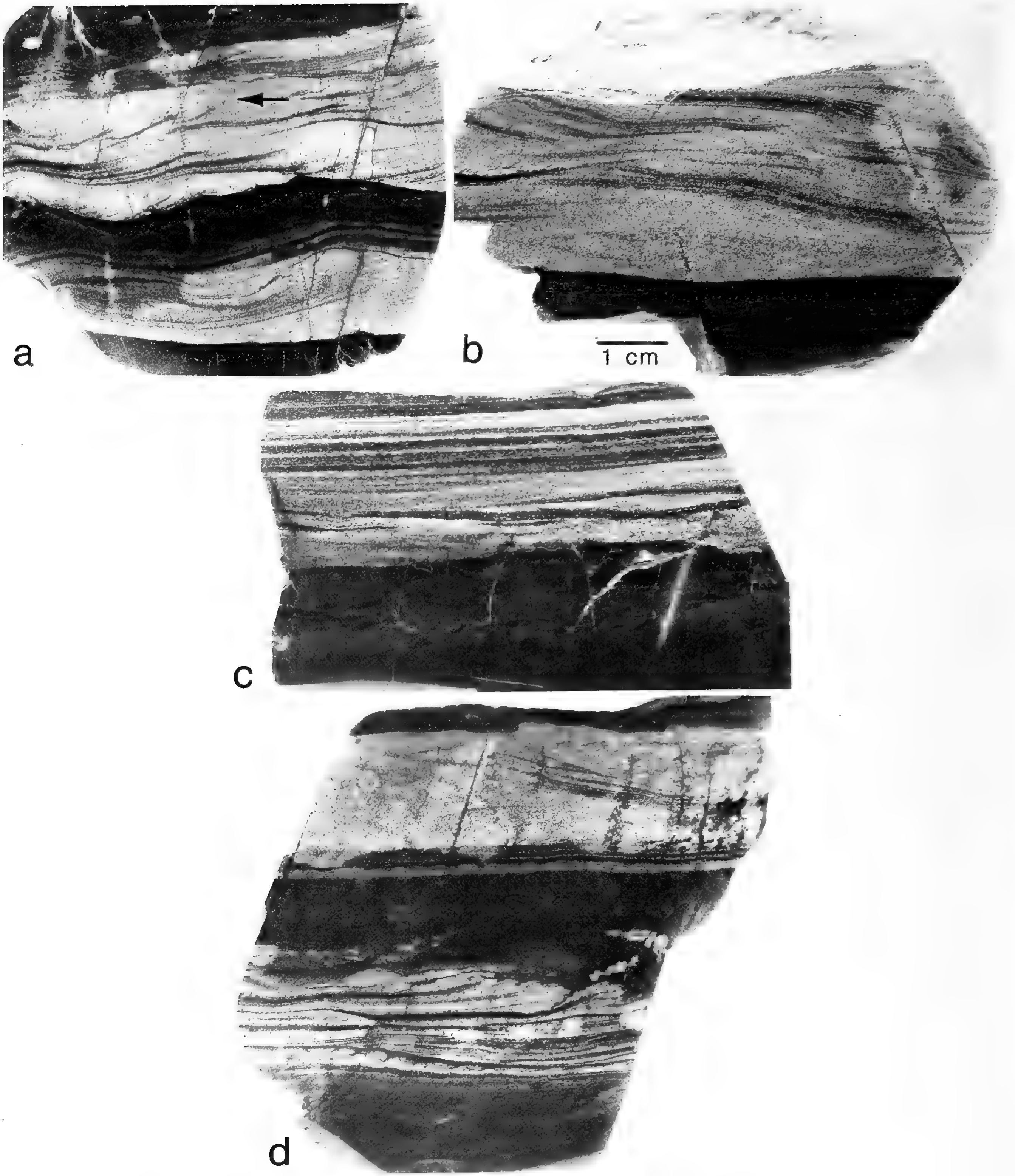

FIGURE 58.—Thin, moderately graded sandstone layers that suggest evidence of turbidite and also tractive-current origin. Strata almost entirely laminated, some showing flaser-like stratification (upper in *a*, lower in *d*), wavy-ripple bedding (lower in both *a* and *d*), cross-lamination (*b*), and alternating sequences of planar-horizontal and ripple laminations (*c*). Localities (Figure 2): *a,d* = site 50; *b* = site 49; *c* = site 55. Scale bar applies to all components.

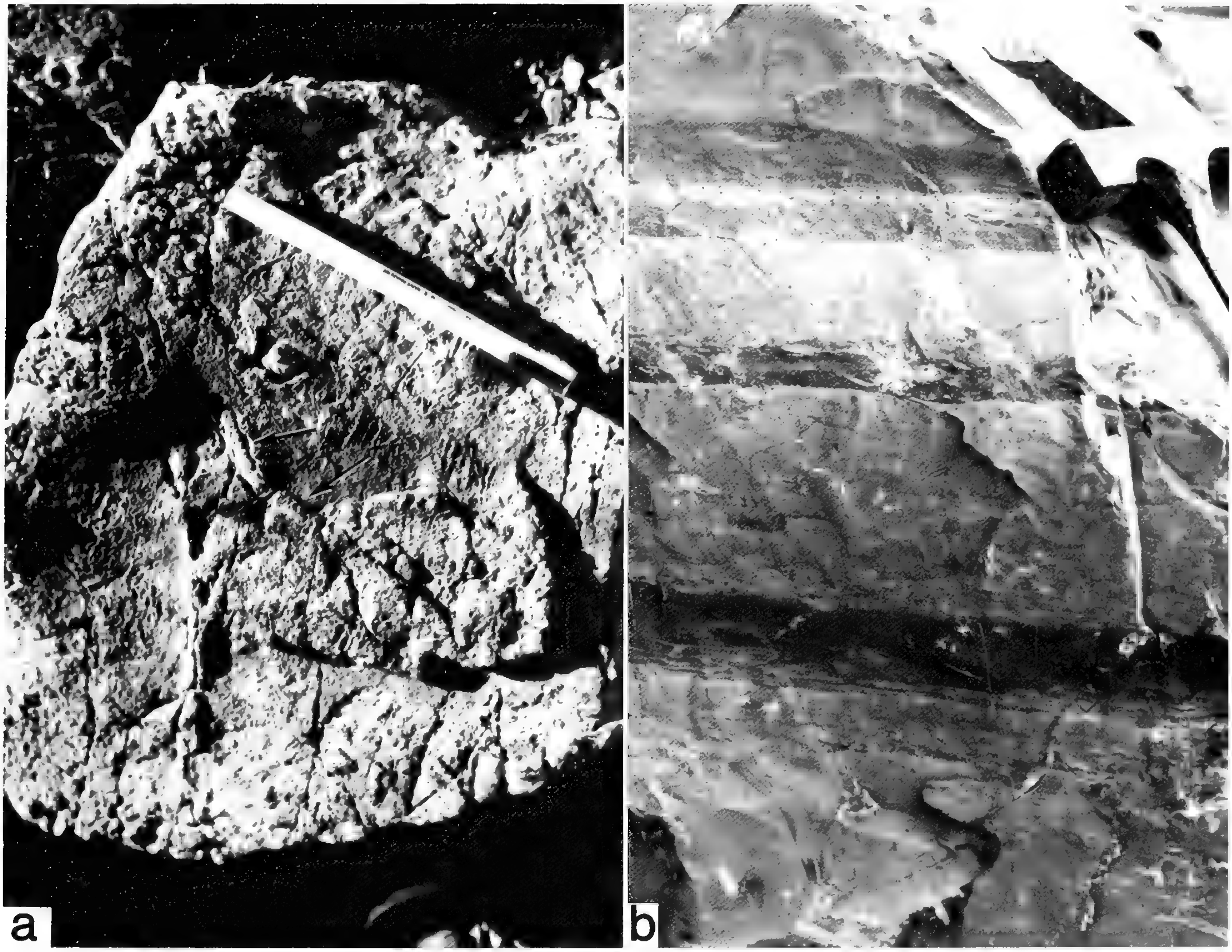

FIGURE 59.—*a*, Worm burrows preserved on extensively reworked bedding surface; pen is 16 cm long. *b*, Even-bedded, sharp based-sharp topped, fine-grained, tuffaceous layers. Absence of internal structures may possibly be the result of extensive biogenic reworking throughout beds; hammer head is 17 cm long. Localities (Figure 2): *a* = site 19; *b* = site 55.

in this region were important and frequent. Moreover, the bottom-currents were apparently sufficiently strong so that the original turbidite sands could be redistributed laterally, often with only modest or no bioturbation.

TURBIDITE TO REWORKED-SAND CONTINUUM.—The reworking of sands was primarily by physical processes capable not only of disrupting the original vertical sequence of turbidite bedform divisions and forming wavy and ripple bedding (Figure 62*a,b*), but also of producing a discontinuous lateral extension and pinch-out of strata (Figure 62*c*). Pinch-out and development of relatively clean sandy lenses (such as starved ripples) may be observed within short stretches of exposed section at many outcrop localities. Thus, the majority of thin sandy strata such as those in Figure 62, which on cursory observation appear to be Ĉ-to-E turbidites, are more reasonably interpreted as partially to thoroughly current-reworked turbidites. On the basis of their characteristics, these layers are not distal turbidites, and it does not appear that the original gravity-flow units were emplaced beyond the base of slope.

Current-reworked turbidites, overall, comprise more than half of the thin sandy strata in the Caledonia Formation, and they also constitute a substantial proportion of sandy layers in the tuffaceous-rich series on St. Croix. The examples of Cretaceous strata illustrated in this monograph are petrologically diverse. An inventory of all observed attributes enables us to postulate a rational continuum of sandy deposits that includes complete turbidites, through a series of partially to

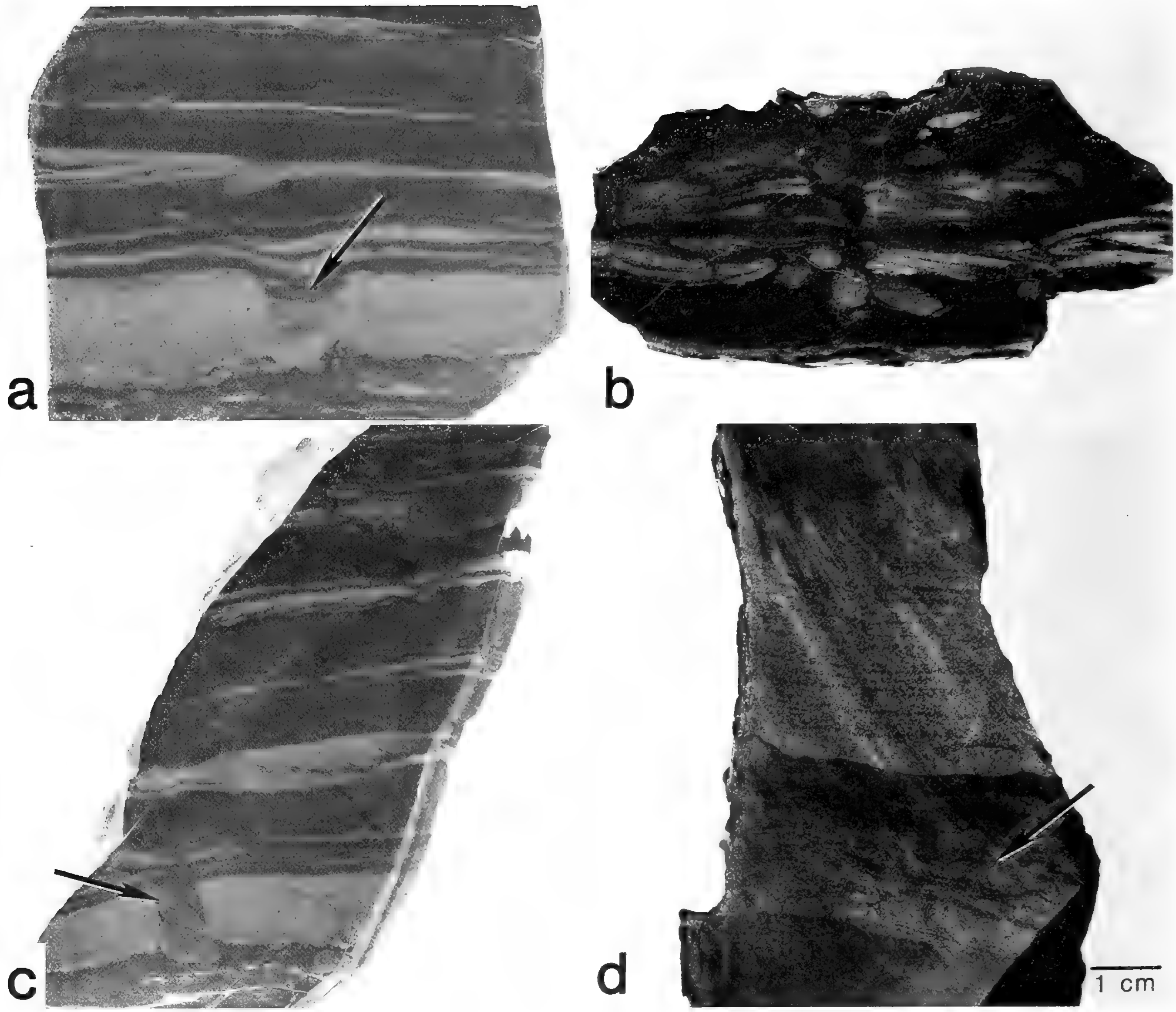

FIGURE 60.—Many of the thin sandstone strata of poorly or undefined origin (some perhaps current-reworked turbidites) show various types of organic structures produced by organisms that have deformed original stratification (arrows). Burrowing and grazing by some organisms affect upper stratal surface (*a*) or may be vertically oriented (*c*), and sometimes disturb several layers (*b,d*). Localities (Figure 2): *a–c* = site 55; *d* = site 42. Scale bar applies to all components.

thoroughly current-reworked turbidites, and finally to deposits whose petrology records primarily a tractive origin (Figure 63). The ultimate lithofacies in this scheme are those in which all original sediment gravity-flow structures, bedforms, and sedimentary fabric have been eradicated and replaced by new ones recording the effects of erosion and a subsequent bottom current transport mode.

Conclusions

This sedimentological study of the Late Cretaceous volcaniclastic rocks on St. Croix reveals a remarkable diversity of sandy lithofacies. The petrological approach used is a descriptive one emphasizing sedimentary structures and bedforms, and indicates that a natural continuum of sandy lithofacies exists between deposits emplaced by downslope-directed, gravity-driven flows and tractive bottom-current processes. Relatively few layers are either distinct turbidites or of entirely tractive origin. Rather, most strata are either turbidite-like or appear bottom-current related, with these latter being recognized as transitional, or variant, bedding types. No systematic vertical-temporal changes in proportion of sandy lithofacies were observed in outcrop sections at most localities.

An overall inventory of sediment types indicates that the

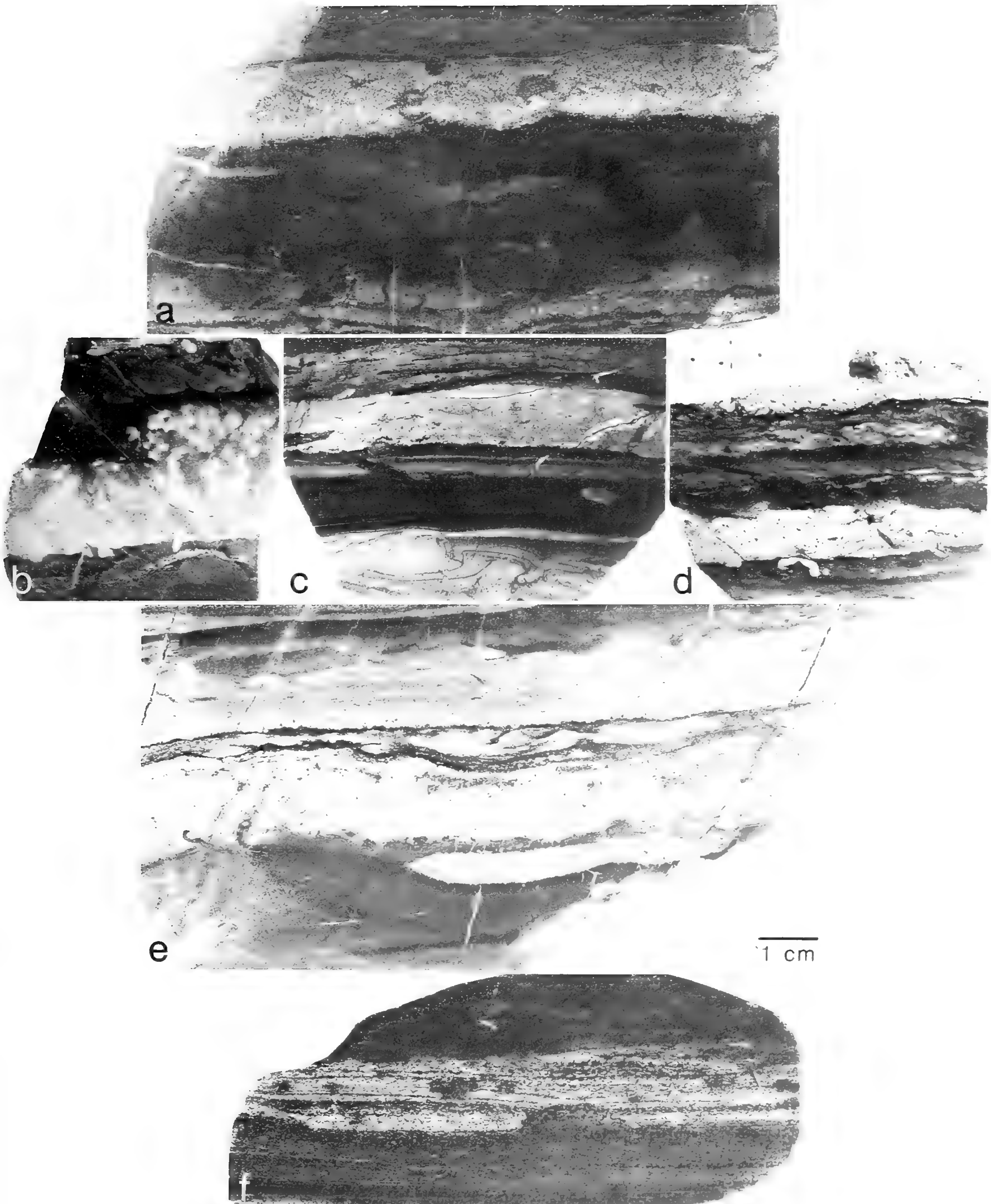

FIGURE 61.—Polished sections showing evidence of extensive bioturbation in thin sandstone strata of poorly defined origin (including some reworked turbidites). Structures by organisms also noted in fine-grained layers between sandstone strata. Localities (in Figure 2): *a* = site 55, *b* = site 43; *c,e* = site 50; *d* = site 53; *f* = site 17. Scale bar applies to all components.

FIGURE 62.—Thin, laminated, sandstone strata showing some features commonly associated with turbidites (graded bedding and basal erosional markings in *a*), but many lack the accepted, orderly, vertical turbidite sequence of A to E bedform divisions. Tractive current transport is recorded by foreset and wavy-ripple bedding and concentrations of heavy minerals (*b*). Discontinuous bedding and pinch-out also commonly observed. Sandy units, such as those in *b* and *c*, typical of most sandstone layers observed in Caledonia Formation in St. Croix and Buck Island and also some sections of the Judith Fancy Formation and other Cretaceous tuffaceous units in St. Croix. These sandy layers are probable reworked turbidites. Localities (Figure 2): *a* = site 3; *b* = site 19; *c* = site 29. Pen is 14 cm and hammer is 28 cm long.

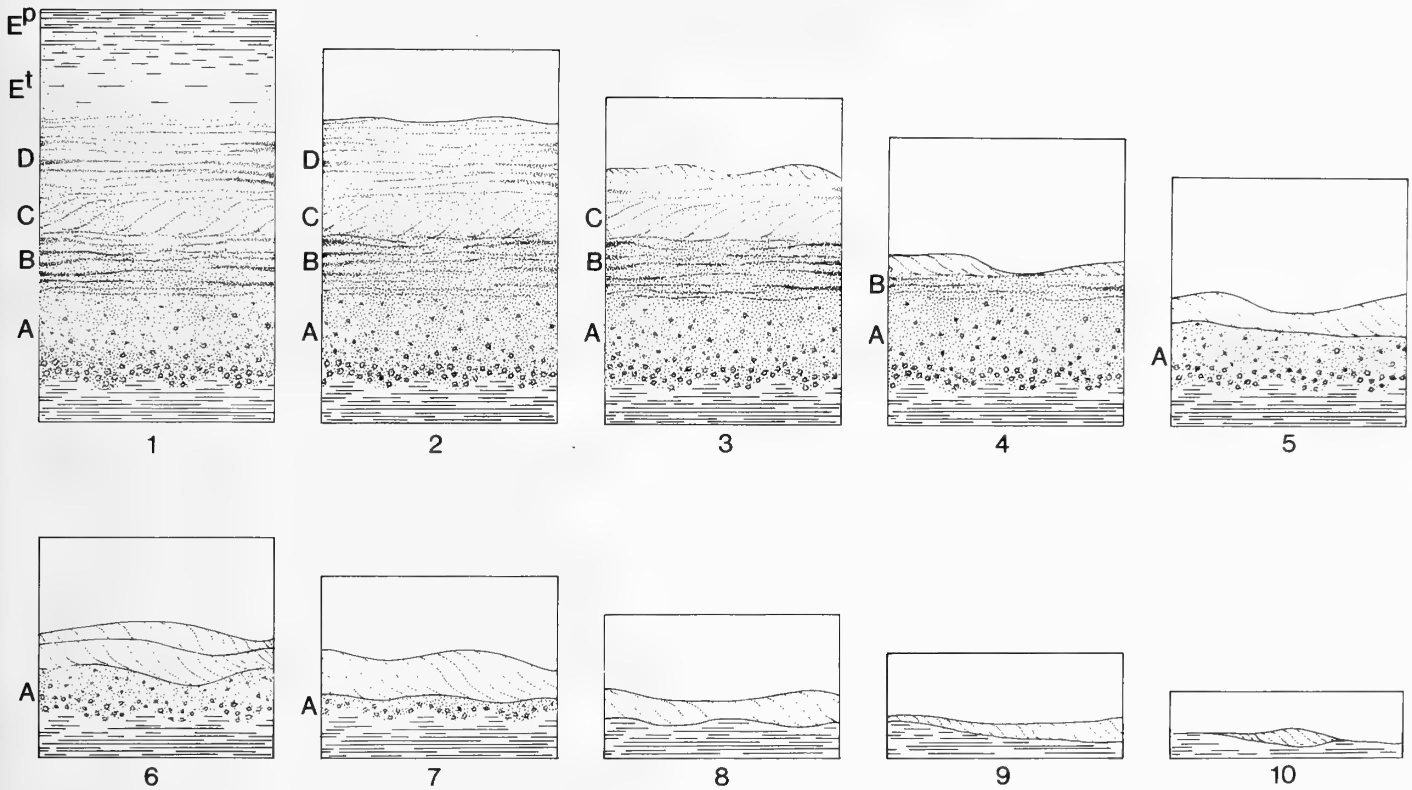

FIGURE 63.—Scheme showing possible continuum of structures that could result from reworking of sandy layer originally emplaced as complete A–E turbidite (1, at left). Reworking would result in partially eroded (2) and redeposited turbidite (variant layer) series (3–7), to completely remolded and entirely foreset laminated (8, 9) and discontinuous (10) layers. Stratal types 7 to 10 are end-products of reworking by bottom currents. Note progressive downward erosion and lateral disruption of original turbidite layer. Actual examples presented in this monograph that could be used to illustrate this series as follows: 1 = Figure 39*a*; 2 = Figure 28*a*; 3 = Figure 56*a,b*; 4–7 = Figure 53*b*; 8 = Figure 55*b*; 9 = Figure 62*b*; and 10 = Figure 45*a*.

lower portion of the variant sand layers often preserves the original basal graded (A) turbidite division, while the mid and upper parts of such layers display structures more typically associated with tractive transport. The continuum of bedding sequences presented herein (Figure 63) is interpreted as a genetic organization of sand types: volcaniclastic sands were initially emplaced by downslope gravity transport, and subsequently reworked by bottom currents.

This investigation indicates that the sandy deposits were emplaced in a proximal setting, perhaps in lower-slope aprons, rather than in more distal and better organized submarine fan lobes or basinal environments. This more proximal slope interpretation is based primarily on the assemblage of selected facies including slides, slumps, coarse debris flow deposits, coarse and complete (A to E) turbidites, and sand-flow layers. Prevailing southward-directed transport directions are measured from structures in sediment-gravity-flow deposits. At the same localities, predominant westwardly (but not uniformly oriented) transport directions are based on measurements from features formed by bottom currents. This near-perpendicular divergence of paleocurrent directions is a strong argument indicating that, after downslope transport, turbidites and the associated layers show reworking by tractive processes. Sands were probably redistributed along bathymetric contours.

Field and petrologic data accumulated herein suggest that the volcaniclastic Cretaceous deposits likely accumulated in a tectonically active, island-arc setting as postulated by earlier workers (Whetten, 1966b; Speed et al., 1979). The paleogeographic position in the Late Cretaceous of the sea-floor sediment presently constituting St. Croix and the St. Croix Ridge remains uncertain. The geographic position of this region relative to the paleo-Atlantic and what was to become the northeastern Caribbean is indicated in a very general way in studies by Sclater et al. (1977, figs. 15, 16), Pindell and Dewey (1982), Burke et al. (1984, fig. 7), Ghosh et al. (1984, fig. 10), Mattson (1984, fig. 4) and others. The rocks, in any case, record evidence of syndepositional deformation of sedimentary and biogenic structures and of the original fabric by intense tectonic and volcanic imprint in the Late Cretaceous and early Tertiary.

The paleocurrent analyses provide insight into deep-water circulation patterns during the Late Cretaceous in this part of the paleo-Caribbean. Although not consistent, the predominant

paleocurrent trend is to the west. This bottom-water flow trend roughly parallels the westerly surface circulation postulated for this region between 100 and 65 million years ago by Berggren and Hollister (1974, fig. 16). The ubiquitous bioturbation recorded in current-reworked sandy layers and interbedded mudstones is an additional indication that circulation above the sea floor was not restricted and that bottom waters were not extensively anoxic (cf. Simoneit, 1986, fig. 9).

The generality proposed by Shanmugan and Moiola (1982), that most sequences rich in turbidites and winnowed-reworked turbidites closely correspond to global lowstands of paleo-sealevel, does not apply in this instance. On the contrary, it would appear that bottom-water circulation, presumably of thermohaline origin, prevailed during the Late Cretaceous, a period of high sea level. Currents sweeping the sea floor were vigorous and of sufficiently high energy to rework turbidites, even those composed of coarse sand.

The validity of the turbidite-to-tractive deposit continuum presented herein could be tested experimentally. It should be possible, for example, to observe the influence of bottom currents on sandy turbidites in flumes, and to quantify flow conditions required to partially, and then completely, remold such layers by tractive processes. Observations, albeit indirect, relating to this phenomenon already exist. For example, evidence of turbidites reworked by bottom currents are preserved in modern oceans (Heezen and Hollister, 1964; Stanley, 1969, fig. 9), particularly where their western margins are subjected to and influenced by geostrophically driven contour-following currents (Tucholke and Ewing, 1974; Hollister and McCave, 1984; Kuijpers and Duin, 1986). Further examination of sedimentary structures, bedforms, and textures in sand layers from continental rise cores off the U.S. East Coast, for example, may reveal variant lithofacies comparable to those of St. Croix described in this contribution.

The implication here is not that the thousands of turbidite studies made to date need reinterpretation. On the other hand, it would seem reasonable that observations made in this study are not unique to St. Croix, and could thus be applied elsewhere. It would be useful to compare observations from the Cretaceous sandy rocks illustrated in this investigation with other formations in the modern and rock record where sandy turbidites appear petrologically anomalous or where a gravity-emplaced interpretation seems forced or remains questionable.

Twenty years ago Ph.H. Kuenen (1967:241) ended his valuable treatise reviewing the emplacement of flysch-type sand beds with the apocalyptic statement that "hasty substitution of turbidity currents by normal currents is like jumping from purgatory, where there is hope, into hell, where there is none." This view needs to be tempered. Turbidity currents are not in question: they do occur, they are clearly a major depositional process in the marine environment, and even in the Recent have been shown to account for the displacement of sand from shallower environments to the deep sea floor. But in view of the many documented observations in the modern and rock record, a minimizing or ruling out of the potentially important role of tractive processes by deep currents is unrealistic and untenable. Continuing to refine interpretations of sand-layer transport would enhance the accuracy of paleogeographic reconstructions and paleobasin analyses. To overlook the possible interaction between bottom currents and turbidity currents would only serve to retard our understanding of deep-sea sedimentation.

Literature Cited

Anketell, J.M., and J.P.B. Lovell
1976. Upper Llandoverian Grogal Sandstones and Aberystwyth Grits in the New Quay area, Central Wales: A Possible Upwards Transition from Contourites to Turbidites. *Geological Journal,* 11:101–108.

Bailey, E.B.
1930. New Light on Sedimentation and Tectonics. *Geological Magazine,* 67:77–92.
1936. Sedimentation in Relation to Tectonics. *Geological Society of America Bulletin,* 47:1713–1726.

Bell, H.D.
1942. Density Currents as Agents for Transporting Sediments. *Journal of Geology,* 50:512–547.

Berggren, W.A., and C.D. Hollister
1974. Paleogeography, Paleobiogeography and the History of Circulation in the Atlantic Ocean. *In* W.W. Hay, editor, Studies in Paleo-Oceanography. *Society of Economic Paleontologists and Mineralogists Special Publication,* 20:126–186

Bouma, A.H.
1962. *Sedimentology of Some Flysch Deposits.* 168 pages. Amsterdam: Elsevier Publishing Company.
1973. Fossil Contourites in Lower Niesenflysch, Switzerland. *Journal of Sedimentary Petrology,* 42:917–921.

Bouma, A.H., and C.D. Hollister
1973. Deep Ocean Basin Sedimentation. *In* G.V. Middleton and A.H. Bouma, editors, *Turbidites and Deep-Water Sedimentation,* pages 79–118 [short course]. Los Angeles: Pacific Section of the Society of Economic Paleontologists and Mineralogists.

Burke, K., C. Cooper, J.F. Dewey, P. Mann, and J.L. Pindell
1984. Caribbean Tectonics and Relative Plate Motions. *In* W.E. Bonini, R.B. Hargraves, and R. Shagam, editors, The Caribbean-South American Plate Boundary and Regional Tectonics. *Geological Society of America Memoir,* 162:31–63.

Case, J.E., T.L. Holcombe, and R.G. Martin
1984. Map of Geologic Provinces in the Caribbean Region. *In* W.E. Bonini, R.B. Hargraves, and R. Shagam, editors, The Caribbean-South American Plate Boundary and Regional Tectonics. *Geological Society of America Memoir,* 162:1–30.

Cedarstrom, D.J.
1950. Geology and Ground-Water Resources of St. Croix, Virgin Islands. *U.S. Geological Survey Water Supply Paper,* 1067: 117 pages.

Cohen, J., R. Manz, and D. Nachman
1974. Geology of Grass Point. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication,* 5:166–167. Christiansted, St. Croix: Fairleigh Dickinson University.

Curth, P.J., S. Frost, L.C. Gerhard, and H.G. Multer
1974. Studies of Pre-Holocene Cenozoic Carbonate Rocks of St. Croix: A Progress Report. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication,* 5:155–158. Christiansted, St. Croix: Fairleigh Dickinson University.

Friedman, G.M.
1984. Field Trip and Guide to Deep-Water Gravity-Displaced Deposits Marginal to the Shelf Edge of the Now-Vanished Proto-Atlantic (Iapetus) Ocean in East-Central New York. *The Compass of Sigma Gamma Epsilon,* 61:181–204.

Gerhard, L.C., S.H. Frost, and P.J. Curth
1978. Stratigraphy and Depositional Setting, Kingshill Limestone, Miocene, St. Croix, U.S. Virgin Islands. *American Association of Petroleum Geologists,* 62:403–418.

Ghosh, N., S.A. Hall, and J.F. Casey
1984. Seafloor Spreading Magnetic Anomalies in the Venezuelan Basin. *In* W.E. Bonini, R.B. Hargraves, and R. Shagam, editors, The Caribbean-South American Plate Boundary and Regional Tectonics. *Geological Society of America Memoir,* 162:65–80.

Hampton, M.A.
1972. The Role of Subaqueous Debris Flow in Generating Turbidity Currents. *Journal of Sedimentary Petrology,* 42:775–793.

Heezen, B.C., and C.D. Hollister
1964. Deep-Sea Current Evidence from Abyssal Sediments. *Marine Geology,* 1:141–174.
1971. *The Face of the Deep.* 659 pages. New York: Oxford University Press.

Heezen, B.C., C.D. Hollister, and W.F. Ruddiman
1966. Shaping of the Continental Rise by Deep Geostrophic Contour Currents. *Science,* 152:502–508.

Holcombe, T.L.
1979. Geomorphology and Subsurface Geology West of St. Croix, U.S. Virgin Islands. *In* J.S. Watkins, L. Montadert and P.W. Dickerson, editors, Geological and Geophysical Investigations of Continental Margins. *American Association of Petroleum Geologists Memoir,* 29:353–362.

Hollister, C.D., and B.C. Heezen
1972. Geologic Effects of Ocean Bottom Currents: Western North Atlantic. *In* A.L. Gordon, editor, *Studies in Physical Oceanography,* 2:37–66. New York: Gordon and Breach.

Hollister, C.D., and I.N. McCave
1984. Sedimentation under Deep-Sea Storms. *Nature,* 309:220–225.

Hsü, K.J.
1964. Cross-Laminations in Graded Bed Sequences. *Journal of Sedimentary Petrology,* 34:379–388.

Hubbard, D.K., T.H. Suchanek, I.P. Gill, S. Williams, and J.C. Ogden
1982. Preliminary Investigations of the Fate of Shallow-Water Detritus in the Basin North of St. Croix, U.S.V.I. *Proceedings of the Fourth International Coral Reef Symposium,* 2:383–387.

Hubert, J.F.
1964. Textural Evidence for Deposition of Many Western North Atlantic Deep-Sea Sands by Ocean–Bottom Currents Rather Than Turbidity Currents. *Journal of Geology,* 72:757–785.

Kauffman, E.G., and N.F. Sohl
1974. Structure and Evolution of Antillean Cretaceous Rudist Frameworks. *Verhandlungen der Naturforschenden Gesellschaft in Basel,* 84:399–467.

Kemp, J.F.
1923. *Report to H.H. Hough, Captain, U.S.N., Governor, Virgin Islands.* 47 pages. St. Thomas Naval Station, U.S. Virgin Islands.

Kuenen, Ph.H.
1937. Experiments in Connection with Daly's Hypothesis on the Formation of Submarine Canyons. *Leidsche Geologische Mededeelingen,* 8:327–335.
1938. Density Currents in Connection with the Problem of Submarine Canyons. *Geological Magazine,* 75:241–249.
1953. Significant Features of Graded Bedding. *Bulletin of the American*

Association of Petroleum Geologists, 37:1044–1066.

1958. Turbidity Currents a Major Factor in Flysch Deposition. *Eclogae Geologicae Helvetiae*, 51:1009–1021.

1967. Emplacement of Flysch-Type Sand Beds. *Sedimentology*, 9:203–243.

Kuenen, Ph.H., and A. Carozzi

1953. Turbidity Currents and Sliding in Geosynclinal Basins of the Alps. *Journal of Geology*, 61:363–373.

Kuenen, Ph.H., and F.L. Humbert

1969. Grain Size of Turbidite Ripples. *Sedimentology*, 13:253–261.

Kuenen, Ph.H., and H.W. Menard

1952. Turbidity Currents, Graded and Non-Graded Deposits. *Journal of Sedimentary Petrology*, 22:83–96.

Kuenen, Ph.H., and C.I. Migliorini

1950. Turbidity Currents as a Cause of Graded Bedding. *Journal of Geology*, 58:91–127.

Kuenen, Ph.H., and J.E. Sanders

1956. Sedimentation Phenomena in Kulm and Flozleeres Graywackes, Sauerland and Oberharz, Germany. *American Journal of Science*, 254:649–671.

Kuijpers, A., and E.J.Th. Duin

1986. Boundary Current-Controlled Turbidite Deposition: A Sedimentation Model for the Southern Nares Abyssal Plain, Western North Atlantic. *Geo-Marine Letters*, 6:21–28.

Lidz, B.H.

1982. Biostratigraphy and Paleoenvironment of Miocene-Pliocene Hemipelagic Limestone: Kingshill Seaway, St. Croix, U.S. Virgin Islands. *Journal of Foraminiferal Research*, 12:205–233.

Loftsgarden, J.L., L.C. Hubbell, and A.A. Astarita

1974. Geology of Isaac Point. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands, *West Indies Laboratory Special Publication* 5:167–169. Christiansted, St. Croix: Fairleigh Dickinson University.

Lovell, J.P.B., and D.A.V. Stow

1981. Identification of Ancient Sandy Contourites. *Geology*, 9:347–349.

Mattson, P.H.

1984. Caribbean Structural Breaks and Plate Movements. *In* W.E. Bonini, R.B. Hargraves, and R. Shagam, editors, The Caribbean-South American Plate Boundary and Regional Tectonics. *Geological Society of America Memoir*, 162:131–152.

McKee, E.D.

1966. Significance of Climbing-Ripple Structure. *U.S. Geological Survey Professional Paper*, 550–D:D94–D103.

Meyerhoff, H.A.

1927. The Physiography of the Virgin Islands, Culebra, and Vieques. *New York Academy of Sciences Scientific Survey of Porto Rico and the Virgin Islands*, 4:145–219.

Middleton, G.V., and M.A. Hampton

1973. Sediment Gravity Flows: Mechanics of Flow and Deposition. *In* G.V. Middleton and A.H. Bouma, editors, *Turbidites and Deep-Water Sedimentation*, pages 1–38 [short course]. Los Angeles: Pacific Section of the Society of Economic Paleontologists and Mineralogists.

Multer, H.G., S.H. Frost, and L.C. Gerhard

1977. Miocene Kingshill Seaway—A Dynamic Carbonate Basin and Shelf Model, St. Croix, U.S.V.I. *In* S.H. Frost, M.P. Weiss, and J.B. Saunders, editors, Reefs and Related Carbonates—Ecology and Sedimentology. *American Association of Petroleum Geologists Studies in Geology*, 4:329–352. Tulsa, Oklahoma.

Multer, H.G., and L.C. Gerhard, editors

1974. Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication*, 5: 303 pages. Christiansted, St. Croix: Fairleigh Dickinson University.

Natland, M.L., and Kuenen, Ph.H.

1951. Sedimentary History of the Ventura Basin, California, and the Action of Turbidity Currents. *In* R.D. Russell, editor, Turbidity Currents and the Transportation of Coarse Sediments to Deep Water. *Society of Economic Paleontologists and Mineralogists Special Publication*, 2:76–107.

Ostapoff, F.

1960. On the Mass Transport through the Drake Passage. *Journal of Geophysical Research*, 65:2861–2868.

Pindell, J., and J.F. Dewey

1982. Permo-Triassic Reconstruction of Western Pangea and the Evolution of the Gulf of Mexico/Caribbean Region. *Tectonics*, 1:179–211.

Piper, D.J.W.

1978. Turbidite Muds and Silts on Deep-Sea Fans and Abyssal Plains. *In* D.J. Stanley and G. Kelling, editors, *Sedimentation in Submarine Canyons, Fans, and Trenches*, pages 163–176. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross.

Quin, J.T.

1907. *The Building of an Island.* 106 pages. Christiansted, St. Croix: Chauncy Holt.

Ratte, C.A.

1974. Geology of Green Cay, St. Croix, U.S.V.I. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication*, 5:187–188. Christiansted, St. Croix: Fairleigh Dickinson University.

Reineck, H.E., and I.B. Singh

1975. *Depositional Sedimentary Environments with Reference to Terrigenous Clastics*. 439 pages. Heidelberg, Germany: Springer-Verlag.

Sclater, J.G., S. Hellinger, and C. Tapscott

1977. The Paleobathymetry of the Atlantic Ocean from Jurassic to the Present. *Journal of Geology*, 85:509–552.

Shanmugam, G., and R.J. Moiola

1982. Eustatic Control of Turbidites and Winnowed Turbidites. *Geology*, 10:231–235.

Shanmugam, G., and K.R. Walker

1978. Tectonic Significance of Distal Turbidites in the Middle Ordovician Blockhouse and Lower Sevier Formations in East Tennessee. *American Journal of Science*, 278:551–578.

Simoneit, B.R.T.

1986. Biomarker Geochemistry of Black Shales from Cretaceous Oceans. *Marine Geology*, 70:9–41.

Sohl, N.F.

1976. Notes on Middle Cretaceous Macrofossils from the Greater Antilles. *In* R.A. Reyment and G. Thomel, editors, *Evénements de la partie moyenne du Crétacé*, pages 30.1–30.6. Nice, France: Centre d'Etudes Méditerranéennes, Muséum d'Histoire Naturelle.

Speed, R.C.

1974. Depositional Realm and Deformation of Cretaceous Rocks, East End, St. Croix. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication*, 5:189–200. Christiansted, St. Croix: Fairleigh Dickinson University.

Speed, R.C., L.C. Gerhard, and E.H. McKee

1979. Ages of Deposition, Deformation and Intrusion of Cretaceous Rocks, Eastern St. Croix, Virgin Islands. *Geological Society of America Bulletin*, 90:629–632.

Stanley, D.J.

1968. Graded Bedding—Sole Marking—Graywacke Assemblage and Related Sedimentary Structures in Some Carboniferous Flood Deposits, Eastern Massachusetts. *In* G. DeVries Klein, editor, Late Paleozoic and Mesozoic Continental Sedimentation, Northeastern

North America, *Geological Society of America Special Publication,* 106:211–239.

1969. Sedimentation in Slope and Base-of-Slope Environments. *In* D.J. Stanley, editor, *The New Concepts of Continental Margin Sedimentation,* pages DJS1–DJS25. Washington, D.C.: American Geological Institute.

1981. Unifites: Structureless Muds of Gravity-Flow Origin in Mediterranean Basins. *Geo-Marine Letters,* 1:77–83.

Stanley, D.J., H.D. Palmer, and R.F. Dill

1978. Coarse Sediment Transport by Mass Flow and Turbidity Current Processes and Downslope Transformations in Annot Sandstone Canyon-Fan Valley Systems. *In* D.J. Stanley and G. Kelling, editors, *Sedimentation in Submarine Canyons, Fans, and Trenches,* pages 85–115. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross.

Stow, D.A.V., and J.P.B. Lovell

1979. Contourites: Their Recognition in Modern and Ancient Sediments. *Earth-Science Review,* 14:251–291.

Stow, D.A.V., and D.J.W. Piper

1984. Deep-Water Fine-Grained Sediments: Facies Models. *In* D.A.V. Stow and D.J.W. Piper, editors, Fine-Grained Sediments: Deep-Water Processes and Facies. *Geological Society of London Special Publication,* 15:611–646.

Stow, D.A.V., and G. Shanmugam

1980. Sequence of Structures in Fine-Grained Turbidites: Comparison of Recent Deep-Sea and Ancient Flysch Sediments. *Sedimentary Geology,* 25:23–42.

Swallow, J.C., and L.V. Worthington

1961. An Observation of a Deep Countercurrent in the Western North Atlantic. *Deep-Sea Research,* 8:1–19.

Tucholke, B.E., and J.I. Ewing

1974. Bathymetry and Sediment Geometry of the Greater Antilles Outer Ridge and Vicinity. *Geological Society of America Bulletin,* 85:1789–1802.

Unrug, R.

1977. Ancient Deep-Sea Traction Current Deposits in the Lgota Beds (Albian) of the Carpathian Flysch. *Annales de la Société Géologique de Pologne,* 47:355–370.

1980. Ancient Contourites in the Menilite Beds (Oligocene) of the Carpathian Flysch, Poland. *Annales de la Société Géologique de Pologne,* 50:175–182.

Vila, J.M., P. Andreieff, H. Bellon, and A. Mascle

1986. Tectonique de collage le long d'un accident décrochant, ante-oligocène, est-ouest, dans les Iles Vierges septentrionales (Antilles). *Comptes Rendus de l'Académie des Sciences, Paris,* 302:141–144.

Walker, R.G.

1965. The Origin and Significance of the Internal Sedimentary Structures of Turbidites. *Proceedings of the Yorkshire Geological Society,* 35:1–32.

Whetten, J.T.

1966a. Geologic Map of St. Croix, U.S. Virgin Islands [Map, in one sheet, at a scale of 1:31,680]. *In* H.H. Hess, editor, Caribbean Geological Investigations. *Geological Society of America Memoir,* 98 [fold-out map in sleeve].

1966b. Geology of St. Croix, U.S. Virgin Islands. *In* H.H. Hess, editor, Caribbean Geological Investigations. *Geological Society of America Memoir,* 98:177–239.

1968. Field Guide to the Geology of St. Croix, U.S. Virgin Islands. *In* T.W. Donnelly and J.T. Whetten, editors, *Field Guide to the Geology of the Virgin Islands,* pages 33–65. College of the West Indies, St. Thomas: Fifth Caribbean Geological Conference.

1974. Field Guide to the Geology of St. Croix, U.S. Virgin Islands. *In* H.G. Multer and L.C. Gerhard, editors, Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands. *West Indies Laboratory Special Publication,* 5:129–143. Christiansted, St. Croix: Fairleigh Dickinson University.

Wüst, G.

1958. Die Stromgeschwindigkeiten und Stommengen in der Atlantischen Tiefsee. *Geologische Rundschau,* 47:187–195.

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